GUIDEBOOK TO GEOLOGIC FIELD STUDIES IN RHODE ISLAND AND ADJACENT AREAS

The 73rd Annual Meeting
of the
New England Intercollegiate Geologic Conference
October 16-18, 1981

Sponsored by
Department of Geology
University of Rhode Island
Kingston, Rhode Island 02881-0801

Edited by
Jon C. Boothroyd and O. Don Hermes
University of Rhode Island

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FORWARD

The University of Rhode Island is proud to host for the first time the New England Intercollegiate Geological Conference. This 73rd annual meeting occurs eighteen years after the last conference held in Rhode Island, at which time eight trips were offered. This contrasts with the diversity of the twenty-two trips being run in 1981, which include emphasis on a variety of geologic problems that range from surficial to bedrock studies.

A resurgence in the interest of the bedrock geology of the area has taken place in the past decade; this new interest partly has been stimulated by recent plate tectonic models that emphasize the distinct character and geologic history of the Avalon Terrain of southeastern New England compared with lithotectonic belts to the west. It is increasingly clear that a better understanding of the geology of this part of New England is necessary in order to understand the geological evolution of the Appalachians as a whole. As elsewhere, the geologic history is complex. Recently initiated studies by a number of workers are adding new information to the data base collected by geologists of decades past. So far the results are leading to new and revised interpretations, but even these can be expected to undergo substantial modification as the early studies progress. Eventhough most of the current studies are imcomplete, we hope that the spirit of NEIGC will provide an opportunity for the geologists working in the area to share the results of their on-going studies with students, faculty, and commercial geologists. We seek an atmosphere for a positive exchange of concepts, interpretations, and ideas so that a better understanding of the geology of southeastern New England and the broader surrounding region will emerge.

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Skehan, James W., S.J., Weston Observatory, Boston College
Smith, Paul V., Weston Observatory, Boston College
Zartman, R.E., U.S. Geological Survey (Denver)

ACKNOWLEDGMENT

The editors extend their thanks to numerous University of Rhode Island graduate and undergraduate students for their assistance in the assembly of the NEIGC announcement and this guidebook.

TABLE OF CONTENTS

GENERAL STRUCTURAL SETTING OF RHODE ISLAND AND TECTONIC HISTORY OF SOUTHEASTERN NEW ENGLAND

Patrick J. Barosh[1] and O. Don Hermes[2]

INTRODUCTION

A great deal of new information has been learned about the geology of Rhode Island and the surrounding region since Quinn summarized the geology of the state in 1971. The new data compliment the earlier work of Quinn and others, and offers the opportunity to make new geologic interpretations, as well as allowing a more precise definition of key problems and areas for future study. Extensive geologic quadrangle mapping and stratigraphic studies by the U.S. Geological Survey have been done in eastern Connecticut and eastern Massachusetts, and adjacent offshore surveys have been completed. Geological and geophysical studies sponsored by the U.S. Nuclear Regulatory Commission have been performed by the New England Seismotectonic Study. The Narragansett Basin has been studied as part of a coal investigation program with the support of the U.S. Bureau of Mines. A variety of work has been done by consultants to public utilities, and a number of topical studies have been undertaken by university personnel and students in the region. More reliable radiometric age dates are now available as a result of improved laboratory techniques and better geologic control on the sample localities. New information also is available on fossil localities. Good aeromagnetic and gravity data now exist or are in preparation for most of this region and excellent Landsat images are available. The close match of magnetic and gravity data with surface geology has led to the discovery of important regional features and now provides a way to map through the glacial cover. Moreover, the increased network of seismographs in the region is greatly improving our knowledge of present day tectonic activity.

This new information has greatly altered our understanding of the structure, geologic history, and tectonic development of the region. The region has undergone a long and complex history of sedimentation, igneous activity, metamorphism, and deformation. As the details of these events become better known, we are more able to draw knowledgeable comparisons and contrasts with adjacent lithotectonic belts, which in turn add to our understanding of the role of plate tectonics in the formation of the Appalachian mountain belt.

The purpose of this introduction to the geology of the Rhode Island region is to present a generalized summary of the structural setting and the geologic history as it is now understood, and to show how the individual field guides pertaining to bedrock geology fit into the overall geology. Several articles that include discussion of general evolutionary geologic models for the larger New England region have been published recently and should be of interest to the reader

[1] Department of Geology and Geophysics, Weston Observatory, Boston College, Weston, MA 02193

[2] Department of Geology, University of Rhode Island, Kingston, RI 02881

(e.g., Rast and other, 1976; Osberg, 1978; Skehan and Osberg, 1979; Rast, 1980; Robinson and Hall, 1980; Skehan and Murray, 1980). The brief nature of our summary does not allow mention of many important geologic features, or the citation of all important studies. For this shortcoming, we ask the reader for tolerant understanding.

GEOLOGIC SETTING OF SOUTHEASTERN NEW ENGLAND

Rhode Island lies along the western side of the Southeastern New England platform, a structural block that is in general the same as the Boston platform (Zartman and Naylor, in press), which a larger scale correlates with the Avalon province of Canada (Rast and others, 1976; Williams, 1978). The Southeastern New England platform is separated from the Merrimack province to the northwest by the narrow Nashoba thrust belt, and is overlapped to the south and east by Cretaceous and Tertiary deposits that form the submerged northward extension of the Atlantic Coastal Plain (Fig. 1).

The Southeastern New England platform consists of a late Proterozoic batholithic complex and associated metasedimentary and metavolcanic rocks that were intruded by younger plutons and covered by sediments at various times during the Paleozoic. The sediments are preserved in basins that are largely fault bounded (Fig. 1). These include the Boston Basin, which contains late Proterozoic to Middle Cambrian conglomerate, argillite, and volcanic rock (Kaye and Zartman, 1980; Kaye, 1981), the Narragansett and Norfolk Basins which contain Carboniferous stream deposits that overlie trilobite-bearing Cambrian phyllites (Shaler and others, 1899; Skehan and others, 1979), and offshore basins of Triassic to Jurrassic sandstone, siltstone, and basalt (Ballard and Uchupi, 1975). Locally common are Mesozoic dikes of diabase and lamprophyre.

The composition of the late Proterozoic intrusions ranges from quartz-rich alaskite and granite to diorite or gabbro. They contain xenoliths and large pendants of metasedimentary and metavolcanic rock. The western edge of the batholith is strongly foliated and syntectonically deformed into a series of large folds. These folds generally trend and plunge to the north along the Rhode Island-Connecticut border but trend westward farther south in southeastern Connecticut. The late Proterozoic intrusives generally are much less deformed to the east where they commonly are not foliated, except in local areas where closely spaced shear zones are abundant. The western border of the platform trends to the northeast in Massachusetts where the structure more characteristically exhibits northeast trending faults rather than folds. The dominant fault trends within the platform are to the northeast and north with more easterly trends near the Boston Basin.

The Nashoba thrust belt northwest of the platform forms a major structural discontinuity. The stratigraphy, structural style, and ages of plutons on either side are strikingly different Barosh and Pease, 1977; Barosh and others, 1978a; Zartman and Naylor, in press). The belt forms a major boundary between tectonic blocks across which no stratigraphic correlation has been made. The Nashoba thrust belt is composed largely of pre-Ordovician andesitic to basaltic volcaniclastic rock, now at high metamorphic grade. These rocks are cut by a series of high angle, west-dipping fault slices that are invaded by granitic intrusive rock of Ordovician to Devonian ages (Dixon, 1964; Alvord and others, 1976; Bell and Alvord, 1976;

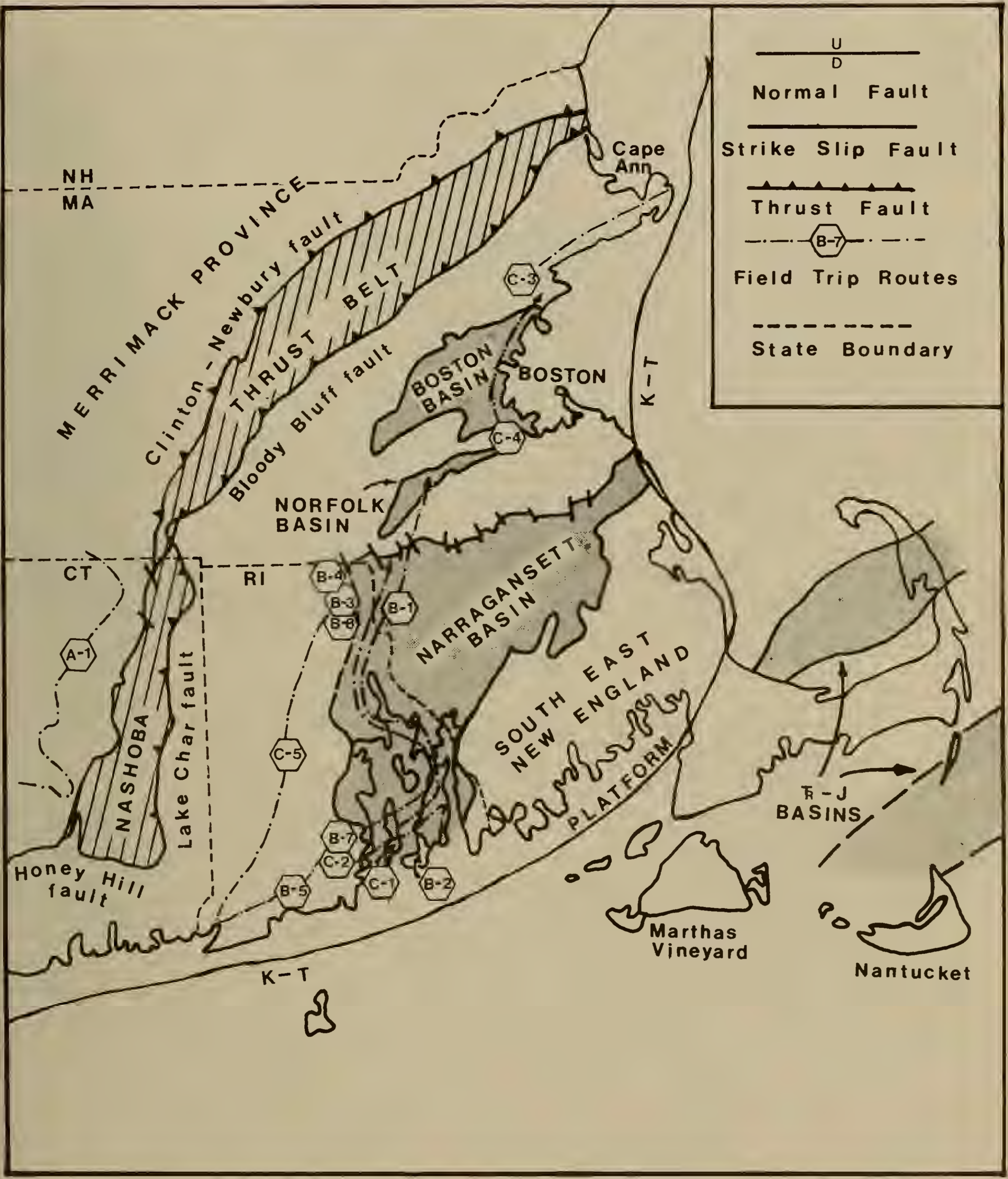

Figure 1. Sketch map of southeastern New England showing major tectonic provinces and basins and general location of field trips.

Zartman and Naylor, in press). The rocks consist of the Marlboro and Nashoba Formations in Massachusetts and the equivalent Quinebaug and Tatnic Hill Formations in Connecticut. The composite section is quite thick, but faulting may have thinned the section to only a few hundred meters just outside the northwest corner of Rhode Island. The main movement within the belt was east over west with a right-lateral component. This appears to have been due to a compressive force acting in a northeast to southwest direction.

The Merrimack province to the west in Connecticut and east-central Massachusetts is formed of a very thick west-dipping and west-topping sequence of pre-Silurian siltstone, graywacke, and shale. These rocks have undergone high-grade metamorphism and are cut by numerous west dipping thrust faults (Peper and others, 1975; Pease and Barosh, Trip A-1). Conversely, the strata in Massachusetts and northward have been interpreted by Robinson and Hall (1980) as a series of folded and refolded nappes, and the structure commonly is referred to as the Merrimack synclinorium. In southeastern New England the term Merrimack geocline seems more appropriate since the rocks form a homoclinal sequence of northwestward dipping strata. Here the structure is cut by long, narrow granitic bodies that apparently intruded some of the earlier thrust faults. The thrust faults cut out much of the section in east-central Connecticut, but offset decreases northward in east-central Massachusetts where the rock is much less faulted.

To the south of the platform, Cretaceous sands and clays and some Early Tertiary sediments form a thick continuous cover offshore, but these occur only as thin scattered patches to the east. A thin, but continuous cover probably existed to the east in the Gulf of Maine but may have been stripped away by glaciers (C. O'Hara, oral comm.).

GEOLOGIC SETTING OF RHODE ISLAND

The structure of Rhode Island consists of a domal batholithic complex on the the west, flanked by the sedimentary Narragansett Basin to the east. Both of these features are unconformably overlapped offshore by a homoclinal sequence of coastal plain deposits (Fig. 2). The general domal structure is defined by the attitude of bedding in Precambrian metasedimentary and metavolcanic rocks variously referred to as the Blackstone Series in Rhode Island, Plainfield Formation in Connecticut, and Westboro Formation in Massachusetts. These strata, which contain assemblages commonly associated with active plate margins (Dreier and Mosher, Trip B-3), lie mainly at the edges of the intrusive-cored dome; they dip to the west in eastern Connecticut, to the north in adjacent Massachusetts, and to the northeast in northeastern Rhode Island. These stratified rocks are feebly metamorphosed and have been deformed by at least two episodes of folding and by low angle thrusting (Dreier and Mosher, Trip B-3). Generally the deformation appears largely syntectonic and many outcrops of the stratified rocks appear to be roof pendants in which bedding is in subparallel alignment with foliation in the intruded granites.

This general domal structure is cut by numerous faults and is distorted by smaller folds. A series of north-trending, north-plunging folds, designated the West Rhode Island fold belt (Barosh, 1976), lies along the Connecticut-Rhode Island border (Fig. 3). These folds are broad and open in the north, but become progressively more compressed to the south where they are overturned and broken by thrust

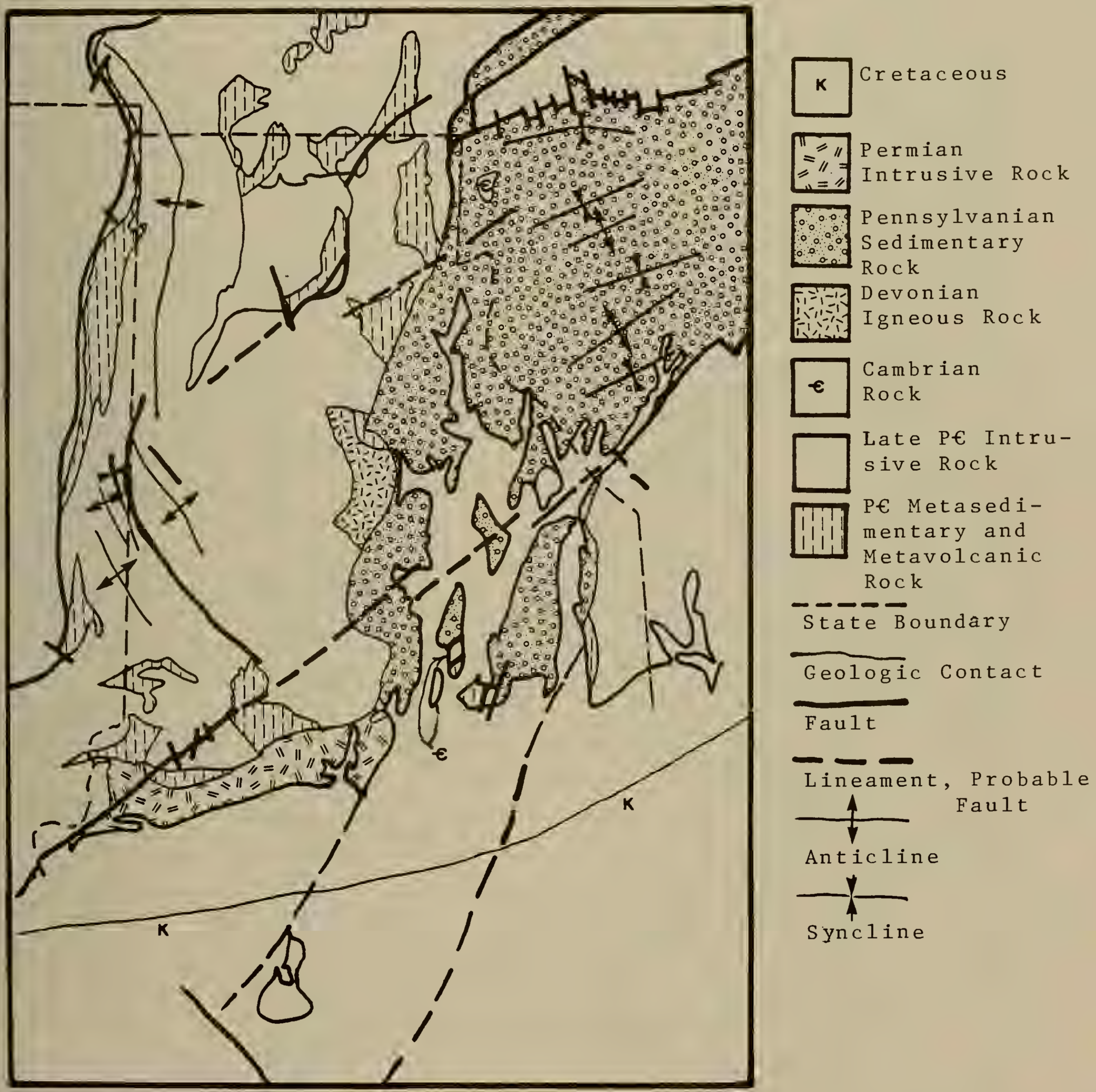

Fig. 2. Sketch map of Rhode Island and vicinity showing major structural features.

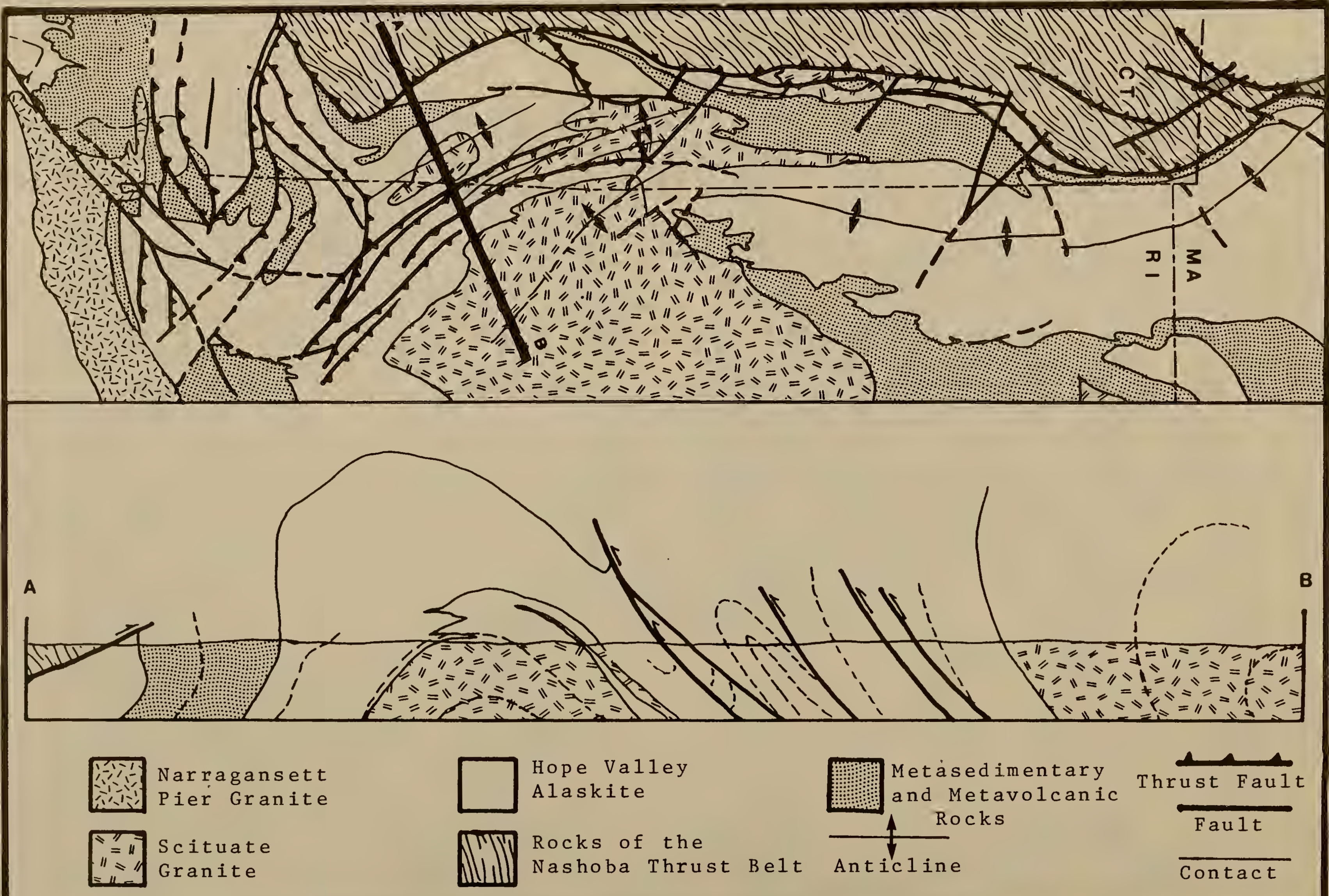

Fig. 3. Sketch map and cross section of West Rhode Island fold belt.

faults. The faults tend to cut out the synclines. The western part of the fold belt swings southwest and west approximately parallel to the Honey Hill fault zone where the folds are overturned to the northwest. The eastern part swings southeast across southwestern Rhode Island and is overturned to the northeast. Both the northwest- and northeast-dipping overturned folds and associated thrust faults appear to have formed at the same time.

Several northeast-trending aeromagnetic and gravity lineaments cross the dome. The distribution pattern and attitude of the Blackstone Series where crossed by these geophysical lineaments suggest that they may be cut by fault zones with a few km of right-lateral offset each. The southern one, the Watch Hill lineament, extends at least through the Carolina Quadrangle as a possible fault zone (Hermes and others, Trip B-5) and projects into the Narragansett Bay where the shape of the bay changes. It and several geophysically defined faults in the bay area may form a major zone of en echelon faults that continue northeastward through Fall River. The interpretation that the Watch Hill lineament is a fault is supported by geophysical ground studies (Schwab and Frohlich, 1976), and by the approximate alignment of the lineament with a fault in Narragansett Basin.

The major geophysical features in the poorly exposed areas southeast of the Watch Hill lineament trend north-northeast (R.K. Frohlich, oral comm.) as they also do in the Narragansett Bay and offshore. This north-northeast direction appears to represent the major structural trend in this area (Collins and McMaster, 1978; McMaster and others, 1980) (Fig. 4). The structural grain north of the lineament appears to be north to north-northwest, as expressed by the trend of contacts and a few known faults.

The Narragansett Basin is a partly fault bounded basin that consists largely of nonmarine conglomerate, sandsone, shale (Burks and others, Trip C-2), and some coal of Carboniferous age (Murray and others, Trip B-7). Horsts of Precambrian sediments, volcanics, and granite are present in the southern part of the bay (Rast and Skehan, Trip B-2; Skehan and Rast, Trip C-1). Rocks of Narragansett Basin are both folded and faulted. The northern part of the basin exhibits an east-northeast-trending group of open folds that reflect a single deformation. In contrast, rocks in the southern part of the basin form tight isoclinal to recumbent north-northeast-trending folds that have been interpreted by some workers to represent multiple episodes of deformation (Burks and others, Trip C-2). The major folds trend generally parallel to the main axis of the basin north of the Watch Hill-Fall River lineament zone. The structure of the poorly exposed parts of the basin is not well known, but much of the west side is faulted. A northeast-trending fault may form the boundary northeast of Fall River and the northern border is cut by numerous small north- to northwest-trending faults (Fig. 1). In addition the basin rocks exhibit a Barrovian type of metamorphism that reached the upper amphibolite facies in the southwestern part of the basin. The grade of metamorphism decreases to the north (Burks and others, Trip C-2; Hepburn and Rehmer, Trip B-1). Isograds of this Alleghenian metamorphic episode are truncated by the Permian aged Narragansett Pier Granite, and the rocks were subjected to local retrograde metamorphism.

The Cretaceous deposits offshore form a northward-facing cuesta of sorts at the inner margin (O'Hara and Oldale, 1980). The consolidated Cretaceous clays and sands exposed at a few places on Block Island may be in place, but those exposed at Martha's Vineyard to the east have been thrust up by glacial push (Kaye, 1964 a, b).

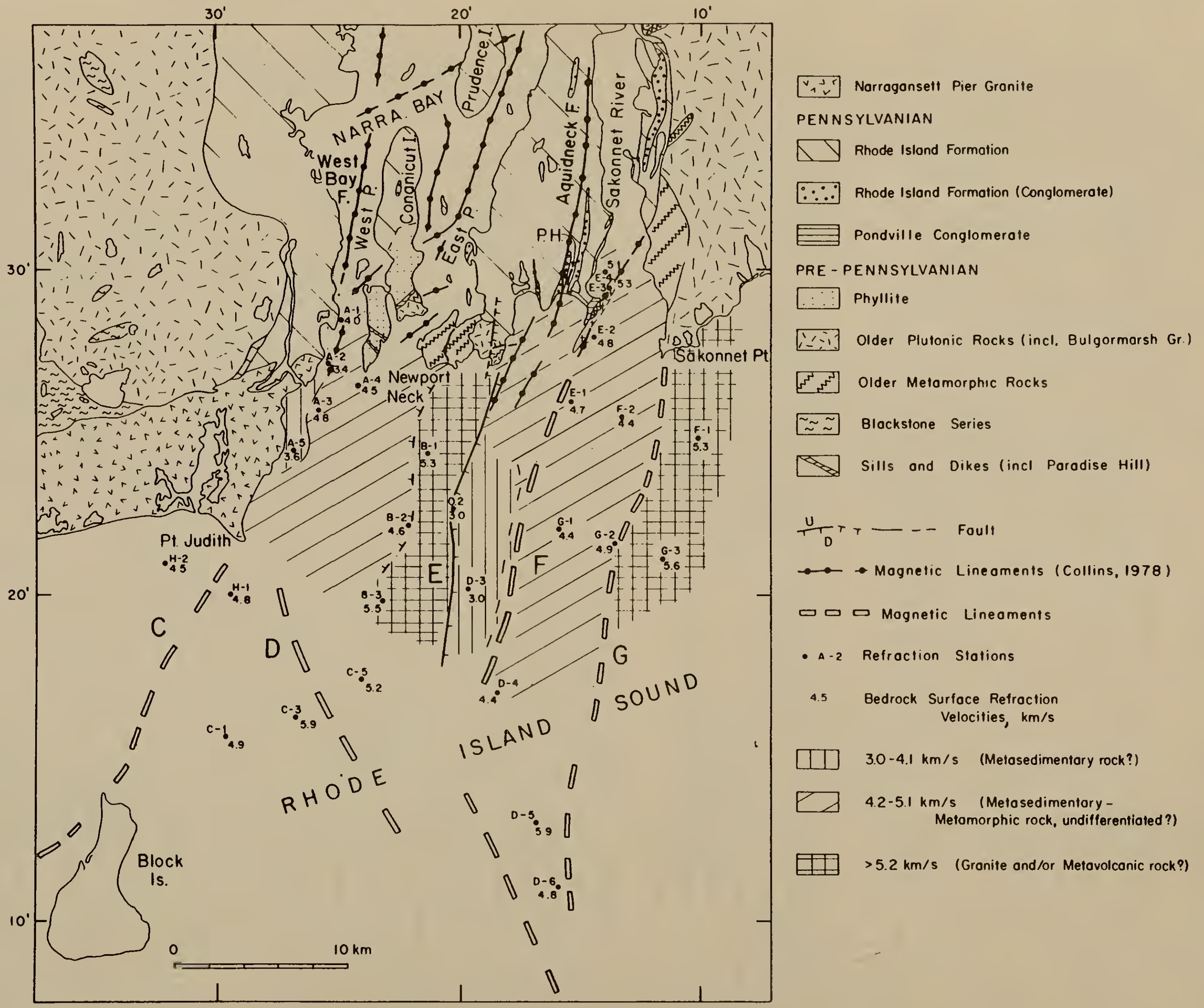

Fig. 4. Geologic and tectonic map of the southern Narragansett Bay and adjacent offshore areas (McMaster and others. 1980).

GEOLOGIC HISTORY

The known geologic history of the southeastern New England platform began in the late Proterozoic when the interbedded Blackstone sequence of quartzite, graywacke, shale, limestone, and volcanic rocks (Carr and Edwards, Trip B-8; Dreier and Mosher, Trip B-3) was intruded by granitic to dioritic rock (Hermes and others, Trip C-5). The late Proterozoic platform rocks in Rhode Island and Connecticut that lie east and south of the Lake Char and Honey Hill fault zones are foliated gneisses and schists. These include the Sterling Group of plutonic rocks and the intruded metasedimentary and metavolcanic rocks. Platform rocks of similar age in eastern Rhode Island and nearby Massachusetts, as well as those adjacent to the Bloody Bluff fault zone in Massachusetts, are less- to non-foliated and have undergone only weak metamorphic recrystallization. The Esmond Group, Newport Granite Porphyry, Dedham Granodiorite, and Milford Granite are the principal Proterozoic plutonic rocks in this part of the platform. Contact metamorphosed xenoliths and roof pendants are all that is left of the intruded country rock.

Especially westward, along the present western boundary of the platform in western Rhode Island and southern Connecticut, the metamorphic fabric of the Sterling Group and related rocks appears to have been imposed syntectonically during emplacement of the plutonic rocks. The Sterling Group rocks are emplaced as sills parallel to foliation and layering in the country rock, and these structures are folded to accommodate the configuration of the Lake Char-Honey Hill fault zones as its trace is warped from south to west in the southeastern corner of Connecticut. The strong metamorphic fabric and high metamorphic grade in this area dies out to the east away from the boundary and also to the northeast in Massachusetts adjacent to the boundary.

These relationships suggest the possibility that a zone of deformation existed in the late Proterozoic along the approximate present trace of the Honey Hill-Lake Char fault zone that served as a precursor to the suture that joined the southeastern New England platform or Avalon plate to North America. Arguments based on radiometric age dating (Zartman and Naylor, in press) and the contrasting lithologies and degree of metamorphism across the boundary argue against juxtaposition of the Southeastern New England platform with tectonic blocks to the west prior to the beginning of the Devonian. Similarly, a maximum age for the North American-Avalonian collision to the north in Maine is interpreted to be 410 m.y. (Gaudette, 1981). On the other hand, Robinson and Hall (1980) have developed a model that juxtaposes the Avalon and North American plates in Ordovician time, whereas on paleomagnetic evidence, Kent and Opdyke (1978) concluded that Avalon rocks of southeastern New England were in the southern hemisphere during the Devonian and were distant from rocks of the North American plate with which they have been associated since Carboniferous time.

Closely following, and perhaps continuous with the emplacement of the late Precambrian plutons and the accompanying tectonic activity, was the deposition of stratified rocks in the Boston Basin. The sequence starts with late Precambrian near shore volcanic rock and conglomerate interbedded with argillite, that grades upward to Middle Cambrian marine argillite (Kaye and Zartman, 1980). The rhyolitic and andesitic volcanic rocks may reflect continuing activity along the eastern edge of the Avalon plate followed by a general transgressive sequence of offshore muds and turbidites. Other volcanic rocks to both the south and north of the Boston Basin also may be Precambrian in age (Naylor, Trip C-4). Fossiliferous carbonate and argillite strata of Cambrian age unconformably overlie Precambrian intrusive rocks at several other places on the platform, such as at Hoppin Hill just east of northern Rhode Island (Dowse, 1950; Shaw 1950; Fairbairn and others, 1967) and at Conanicut and Aquidneck Islands in the southern Narragansett Basin (Skehan and others, 1977; Rast and Skehan, Trip B-2; Skehan and Rast, Trip C-1).

Igneous activity of a generally distinct alkalic to peralkaline nature periodically occurred within the platform during the mid-Paleozoic (Rutherford and Carroll, Trip B-4; Hermes and others, Trip C-5). The mineralogy, textures, and chemistry of these rocks sharply contrast with the Proterozoic plutons which are more calcalkaline in character.

The older of these alkalic rocks range from Late Ordovician to Early Silurian, and include the Cape Ann and Quincy Granites, granites from the Gulf of Maine, and gabbroic bodies at Salem and Nahant (Zartman, 1977; Hermes and others, 1978). These hypersolvus granites and associated mafic rocks appear to be shallow intrusives, and probably were accompanied by volcanic activity. For example, the Quincy Granite appears to grade into rhyolite on its south side (C. A. Kaye, oral comm.), and comagmatic felsic dikes are associated with the Cape Ann pluton. Numerous mafic dikes also cut the Cape Ann rocks at this time (Ross, Trip C-3), and in some cases, there is evidence for the simultaneous coexistence of mafic and felsic magmas (Toulmin, 1964; Dennen, 1976). Other gabbroic plutons also may have been intruded at this stage, including the cumberlandite/gabbroic anorthosite complex of north-central Rhode Island, the Foster Gabbro of west-central Rhode Island (Pope, 1975), the Preston Gabbro (Zartman and Naylor, in press) at the south end of the Nashoba belt in Connecticut, and a probable but unexposed large pluton beneath the western end of Cape Cod (Barosh, and others, 1977b). Ordovician granitic rocks of calcalkaline affinity also intruded the Nashoba and Merrimack blocks (Zartman and Naylor, in press).

A second grouping of generally alkalic rocks range in age from Early to Middle Devonian. In Massachusetts, these include the Wenham Monzonite, Peabody Granite, and the Rattlesnake Hill pluton (Lyons and Kruger, 1976). Southward in Rhode Island, alkalic rocks of the East Greenwich Group and parts of the Scituate Granite Gneiss yield Devonian ages (Hermes and others, Trip C-5). Although generally contemporaneous with Acadian plutons in tectonic blocks to the west, these mid-Paleozoic plutons of the Southeastern New England platform generally maintain a distinct petrologic character.

Volcanic activity still affected the region in the Late Silurian-Middle Devonian as is shown by the variety of volcanic rocks mixed with marine sediments in the Newbury volcanic sequence (Shride, 1976). These occur in an unmetamorphosed fault slice along the contact with the Nashoba thrust belt north of the Boston Basin. Possibly a volcanic chain connected them with the contemporaneous coastal volcanic sequence of eastern Maine. Moreover, the Spencer Hill volcanics of central Rhode Island have been interpreted by Quinn (1971) to be comagmatic with the Devonian-aged Cowesett Granite.

Probably accompaning the mid-Paleozoic magmatic events, was the development of local contact metamorphic aureoles. The folding and faulting that affected the Late Silurian turbidite sequence in the Merrimack block north of Worcester may have developed at this time (Peck, 1976; Smith and Barosh, 1981). Unresolved is whether the low grade metamorphism of the rocks in the Boston Basin occurred in the Precambrian, during the mid-Paleozoic event, or later during Alleghenian time.

The platform may have experienced uplift and extensional faulting that led to the shedding of post-orogenic Late Devonian clastic deposits in the coastal volcanic zone of eastern Maine. Uplift, perhaps with associated extensional faulting, probably occurred on the Southeastern New England platform during the Carboniferous to produce the non-marine conglomerate, sandstone, shale and coal of the Narragansett and Norfolk Basins. These deposits may have overlapped the Nashoba thrust belt as shown by the presence of a fault sliver of Carboniferous rock on its west side in Worcester (Grew, 1973).

The sedimentary rocks in the Narragansett Basin probably were deformed and metamorphosed mostly before the intrusion of the Narragansett Pier and Westerly Granites in the Permian (Burks and others, Trip C-2; Hermes and others, Trip B-5). The highest grade of metamorphism roughly borders the southwestern margin of the basin and drops off to the north. Illite crystallinity studies hint that two Alleghenian thermal events may have occurred (Hepburn and Rehmer, Trip B-1). Although earlier work suggested that Alleghenian deformation and metamorphism was fairly localized, a number of recent studies indicate that it may be more widespread than formerly realized (Zartman and others, 1970; Day and others, 1980; Skehan and Murray, 1980; Dallmeyer, 1981).

The platform, along with the rest of southern New England, underwent uplift and extensional faulting during the Late Triassic and Jurassic as major rifting was initiated across the North Atlantic Basin. Deposition of continental clastic sediments and basalts occurred in local basins like that of the Connecticut Valley and numerous diabase dikes were injected into the older rocks (Ross, Trip C-3). Lamprophyric dikes also occur locally and may be of generally similar age. With the exception of a small fault sliver of fossil-bearing sediments exposed against the Nashoba thrust belt north of Boston (C. A. Kaye, pers. comm.), the remaining Mesozoic basins lie off-shore to the east (Ballard and Uchupi, 1975). During the Mesozoic there was reactivation of the Watch Hill fault zone which cuts the Narragansett Pier Granite as well as some displacement along the high angle faults that cross the Narragansett Basin. A regional tilt to the north, indicated by northward plunging structures and northward decrease in effects of different metamorphic events, also may have accompanied this episode.

The edge of the platform sagged to the south and east during the Late Jurassic and Cretaceous as the North Atlantic Basin continued to open, and an apron of clastic sediments of Cretaceous age was deposited on it. Deposition continued at least into the Early Tertiary (Weed, and others,1974). Post Creteceous movements formed the north to northwest-trending New Shoreham fault just west of Block Island (McMaster, 1971), and may have caused the small north- to northwest-trending faults that cut the Watch Hill fault zone on shore to the north (Hermes and others, Trip C-5).

During the Pleistocene the region was depressed by the weight of the glacial ice. The rebound of the crust that began soon after the ice started its retreat 13,500 years ago has resulted in a regional tilt to the south of about 1m/km. This tilt and the post-glacial rise in sea level have caused the Late Pleistocene shoreline to be deeply submerged off-shore to the south (O'Hara and Oldale, 1980), whereas it rises above the present sea level at the northern edge of the Massachusetts coast.

At present the Narragansett Bay area and adjacent southeastern Massachusetts exhibits mild seismic activity, with earthquakes occurring every few years (Fig. 5).

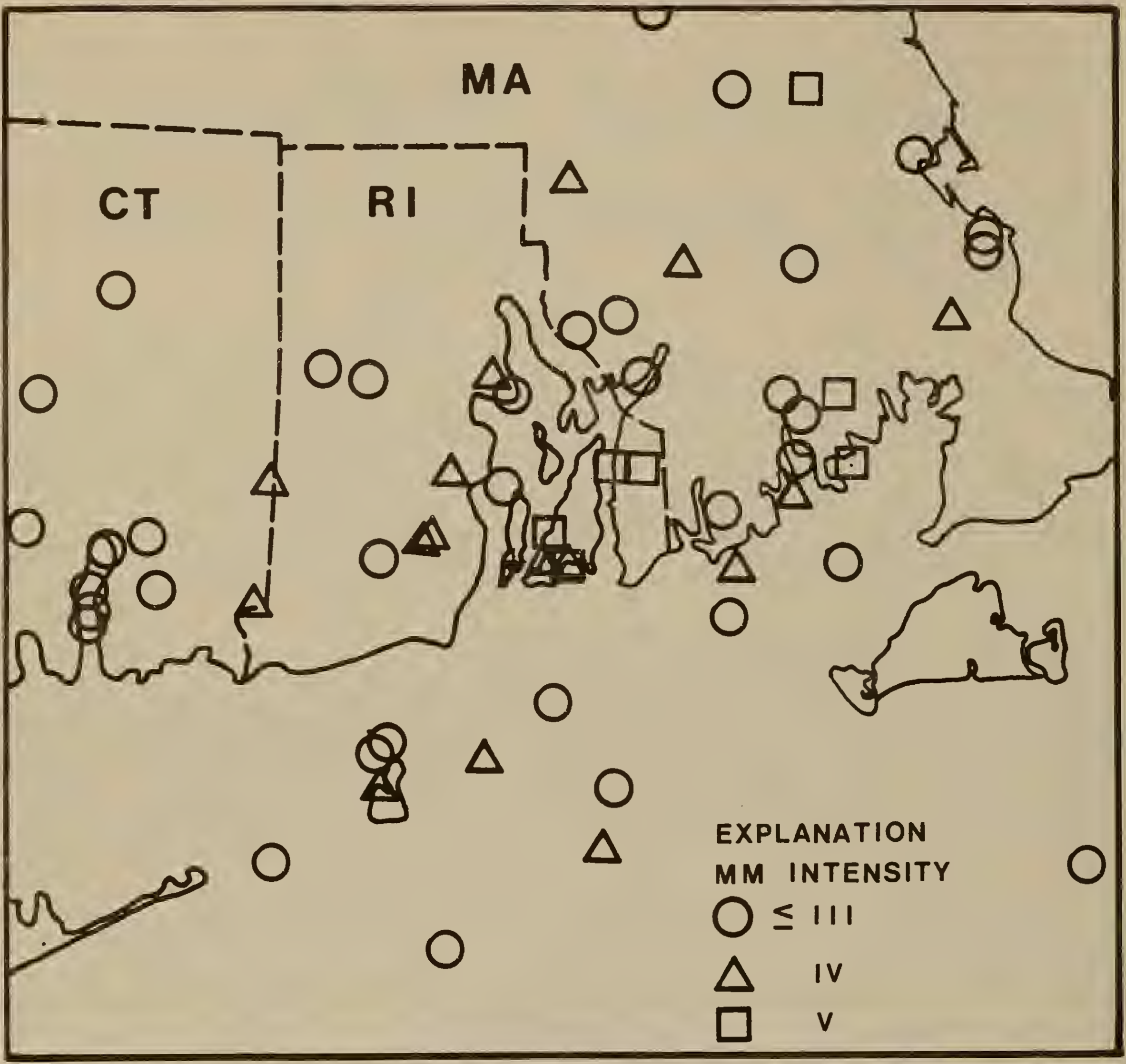

Figure 5. Sketch map of southeastern New England showing epicenters and intensities of historical earthquakes in the region.

The movements causing these earthquakes have yet to be determined, but they may be due to active subsidence in the bay area. Subsidence in the Passamaquoddy Bay area of Maine and New Brunswick appears to be related to the occurrence of earthquakes there (Tyler and others, 1979).

ACKNOWLEDGEMENTS

We gratefully acknowledge the discussions and contributions of many workers in southeastern New England over the past years and regret not being able to cite all of them individually in this short article. We thank M.H. Pease, Jr. and Paul V. Smith for reviewing the manuscript. The work of PJB was supported by the U.S. Geological Survey, 1971 to 1976, and since 1976 by the U.S. Nuclear Regulatory Commission as part of the New England Seismotectonic Study (Contract No. At(49-24)-0291). That of ODH was supported by the University of Rhode Island, the U.S. Geological Survey, and the National Science Foundation (EAR-8025492).

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DISTRIBUTION AND STRUCTURAL SIGNIFICANCE OF THE OAKDALE FORMATION IN NORTHEASTERN CONNECTICUT

by

M.H. Pease, Jr., Geologist
U.S. Geological Survey, ret., Waterville Valley, N.H.

and

Patrick J. Barosh, Weston Observatory
Dept. of Geology and Geophysics, Boston College
381 Concord Road, Weston, MA 02193

INTRODUCTION

Extensive geologic quadrangle mapping in recent years by the U.S. Geological Survey in cooperation with the states of Massachusetts and Connecticut has provided a coherent interpretation of the stratigraphy and structure of a region extending from east-central Massachusetts into northeast Connecticut (Peper and Pease, 1976; Barosh, Fahey and Pease, 1977; and Barosh, 1974 and 1977) (Fig. 1). As mapping progressed in this region, knowledge of the stratigraphy was increased and map units were refined. This new information has necessitated revision of stratigraphic relationships and in many places structural interpretations as presented by previous workers. The most significant advance is recognition that the Oakdale Formation can be traced into Connecticut and is equivalent to strata formerly mapped as part of the Hebron Formation and Scotland Schist. This guide will show the distinguishing lithologic and stratigraphic characteristics of the Oakdale Formation in the region and discuss the structural significance of this improved stratigraphic control. A one day trip does not provide time to adequately trace the Oakdale through Connecticut. Instead, exposures of lithologies representative of the Oakdale and of strata overlying it will be seen south of its type area in southern Massachusetts and along two other general traverses farther south in northeastern Connecticut to demonstrate that the sequence extends southward.

In Massachusetts the Oakdale Formation and younger Paxton Group lie both physically and in apparent right-side-up position stratigraphically beneath the Brimfield Group rocks (Fig. 1). The Brimfield Group is a thick homoclinal west-facing succession that underlies much of south-central Massachusetts and extends across New Hampshire. The Clinton-Newbury fault zone, a major structural discontinuity in Massachusetts, across which no stratigraphic correlation has been possible, separates the Oakdale-Paxton-Brimfield succession from rocks of the Nashoba and underlying Marlborough Formations to the east. The Nashoba and Marlborough continue into Connecticut as the Putnam Group. The Oakdale-Paxton, composed of schistose granulite and metasiltstone respectively, form a belt of strata in eastern Connecticut that have been variously termed Hebron, Scotland and Southbridge Formations (Dixon and Lundgren, 1968; Pease, 1972).

The structural block containing the Paxton-Oakdale (Hebron) sequence in

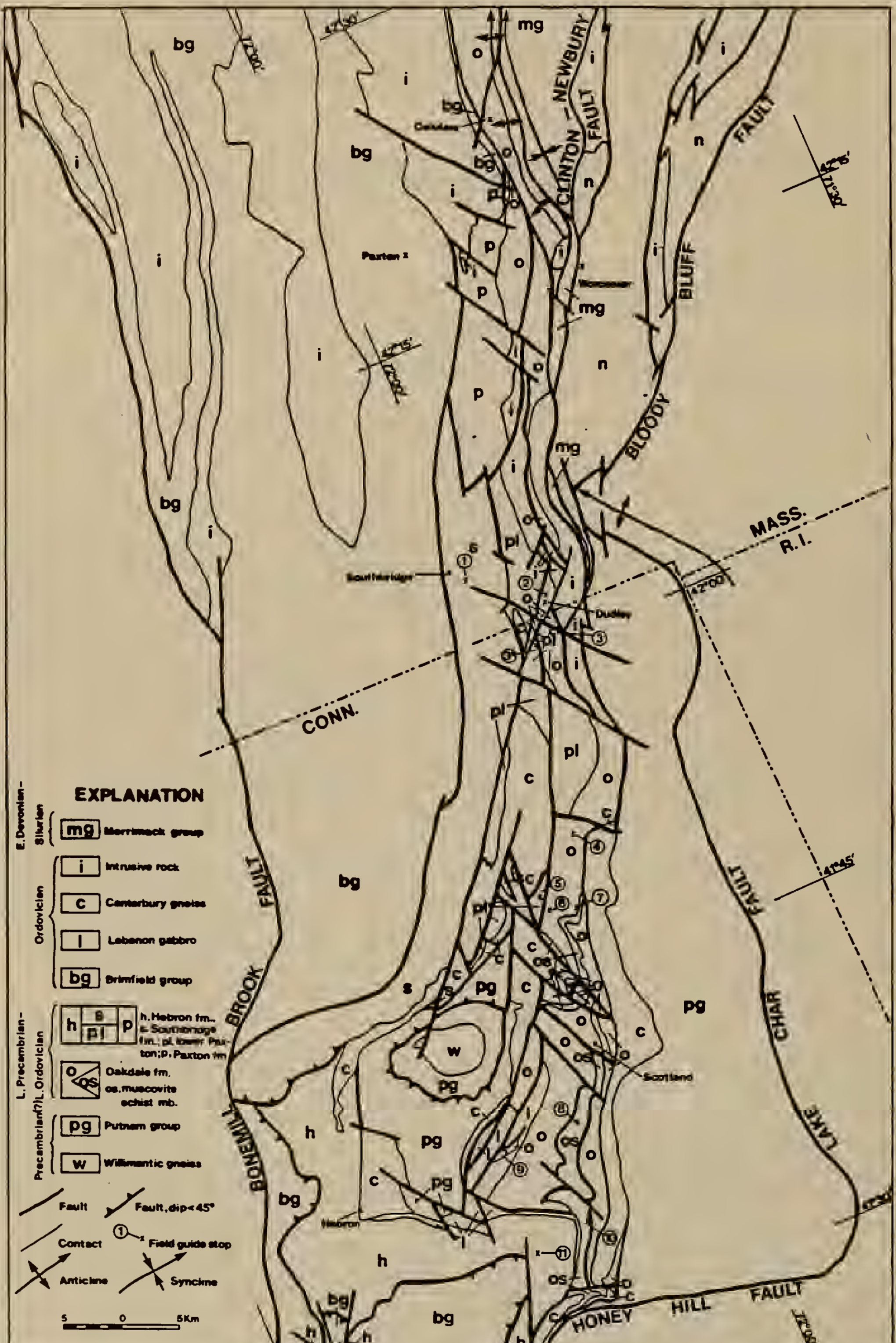

Figure 1. Simplified geologic map of south-central Massachusetts and eastern Connecticut showing distribution of the Oakdale-Paxton sequence of metasedimentary rock.

Connecticut is bounded on the west by the Black Pond fault and on the east by the Clinton-Newbury fault zone. The structural position of the Clinton-Newbury fault zone in Connecticut is invaded and masked by foliated intrusive rock.

HISTORICAL CONTEXT

Emerson's Geologic map (1917) shows that the Brimfield, Paxton and Oakdale extend to the Connecticut state line. To the south in Connecticut this sequence was described as Brimfield Schist and Hebron Gneiss (Gregory and Robinson, 1907; Rodgers and others, 1959). The Oakdale lies east of and structurally beneath the Paxton; the Brimfield lies mostly west of and structurally above the Paxton (Fig. 2) although belts of Paxton also are shown within the eastern part of the Brimfield. Emerson (1917, p. 62) stated that "The Paxton passes in pitching folds beneath the Brimfield" in this area. He also considered the Paxton to be a higher metamorphic grade equivalent of the Oakdale.

During the period 1955-1968 much of eastern Connecticut was mapped at a scale of 1:24,000 by the U.S. Geological Survey in cooperation with the Connecticut Geological and Natural History Survey. As a result of this work, which was summarized by H.R. Dixon and L.W. Lundgren, Jr. (1968), a threefold stratigraphic sequence was established for northeastern Connecticut consisting of Scotland Schist at the top, Hebron Formation in the middle and Putnam Group (Tatnic Hill Formation overlying the Quinebaug Formation) at the base (Fig. 2). The Brimfield Group was considered to be an inverted equivalent of the Tatnic Hill Formation resting structurally on the Hebron.

From 1966 to 1975 detailed geologic mapping was undertaken in the Brimfield area of Connecticut and Massachusetts, beginning in the Eastford quadrangle (Pease, 1972). This work resulted in redefinition of the Hebron Formation and Brimfield Schist of Connecticut and adjacent Massachusetts. It demonstrated that the "folds" of Paxton in the Brimfield are intervals of amphibolite and pyroxene-bearing biotite schist and gneiss within the Brimfield and not part of the type Paxton.

In the Eastford quadrangle report (Pease, 1972) the Hebron Formation was divided into two distinct groups of rocks separated by the northeast-trending Eastford fault. Strata northwest of the fault were named the Southbridge Formation with the type area in Southbridge, Massachusetts, immediately to the north of the Eastford quadrangle where the formation had been mapped by G.E. Moore, Jr. (1978). These strata form the upper part of the Paxton of Emerson. The Hebron Formation and Scotland Schist were restricted to the east side of the fault in the Eastford quadrangle report (Fig. 2).

The Southbridge Formation is a more heterogeneous and generally coarser-grained sequence than the Hebron Formation. The Southbridge consists mostly of dark- and light-gray, well layered, medium- to coarse-grained biotite gneiss and schist with less common amphibolite and sulfidic schist lenses; the Hebron is a medium-gray to greenish-gray, uniformly thin-layered, fine-grained, biotite schistose granulite.

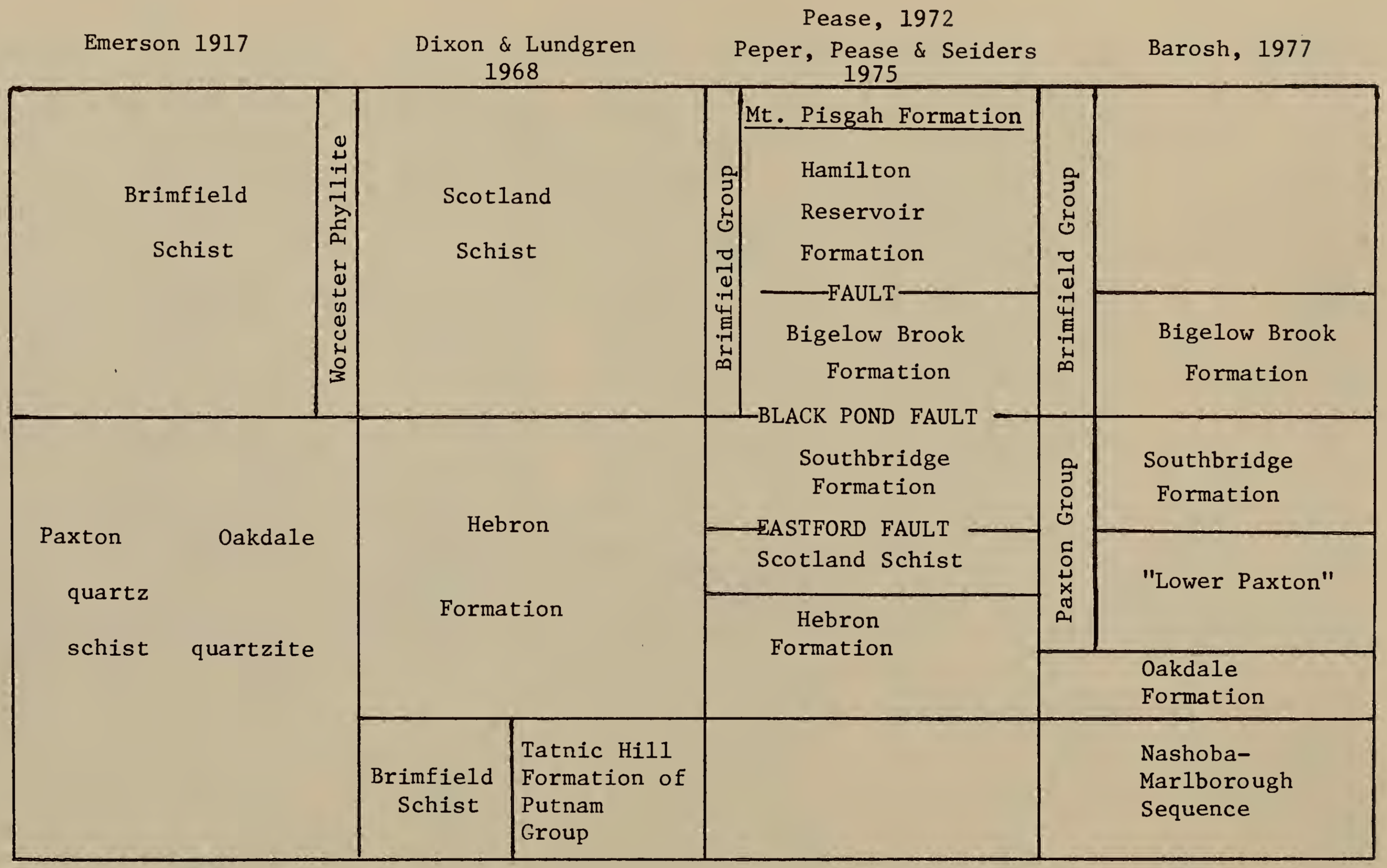

Fig. 2 - Evolution of stratigraphic terminology in central Massachusetts and northeast Connecticut prior to recognition of the Oakdale Formation in Connecticut (not a correlation chart).

Modern geologic mapping of the Oakdale and Paxton strata in adjacent Massachusetts was started in the early 1970's. A program of geologic mapping under the direction of P.J. Barosh, then with the U.S. Geological Survey, was undertaken in the region from Worcester into the northeast corner of Connecticut. In an open-file report on geology of this region (Barosh, 1977), the name Oakdale quartzite was informally changed to Oakdale Formation, on the basis that it is mostly metasiltstone with little or no true quartzite. The Paxton quartz schist was informally redefined as the Paxton Group because the Southbridge-Hebron division, recognized in the Eastford quadrangle, Connecticut, was also recognized in the contiguous Paxton of southeastern Massachusetts. The Oakdale was shown to be older than the Paxton Group rather than equivalent to the Paxton, as per Emerson.

The term Southbridge Formation is retained for the upper part of the Paxton and the remainder of the Paxton above the Oakdale is informally assigned to the "Lower Paxton".

Figure 2 shows the evolution of the stratigraphic nomenclature prior to recognition of the Oakdale Formation in Connecticut.

OAKDALE FORMATION

The Oakdale Formation is an unusually homogeneous calcareous metasiltstone that maintains its character from New Hampshire through Massachusetts to as far south as the Honey Hill fault in Connecticut (Barosh and Pease, 1981). The Scotland, formerly considered a separate formation, now has been demonstrated to be a member within the Oakdale, the most extensive of many pelitic schist intervals within the Oakdale throughout its area of exposure. Figure 3 shows the correlation of stratigraphy in eastern Connecticut and central Massachusetts as it is presently interpreted.

The characteristic and most common lithology of the Oakdale in its type area, Oakdale, Massachusetts (Fig. 1) is a medium-to dark-gray, greenish-gray and purplish-gray metasiltstone that weathers light to medium-gray, greenish or brownish-gray. It consists of "granulose silt-size quartz,plagioclase (oligoclase-andesine) and brown biotite, with minor amounts of chlorite, actinolite, garnet, staurolite, muscovite and calcite" (Peck, 1975). The metasiltstone is well bedded in thin to medium beds, commonly laminated or cross-laminated with a few graded beds. According to Peck, the rock may locally be phyllitic. Included with this dominant lithology are small calcareous lenses and minor but conspicuous lenses of pelitic staurolite-bearing schist. The formation maintains its characteristic metasiltstone grain size regardless of proximity to intrusive rocks and even where it occurs as xenoliths.

SCOTLAND SCHIST MEMBER

The redefined Scotland Schist member of the Oakdale Formation is restricted to the conspicuous band of highly pelitic schist that lies in the

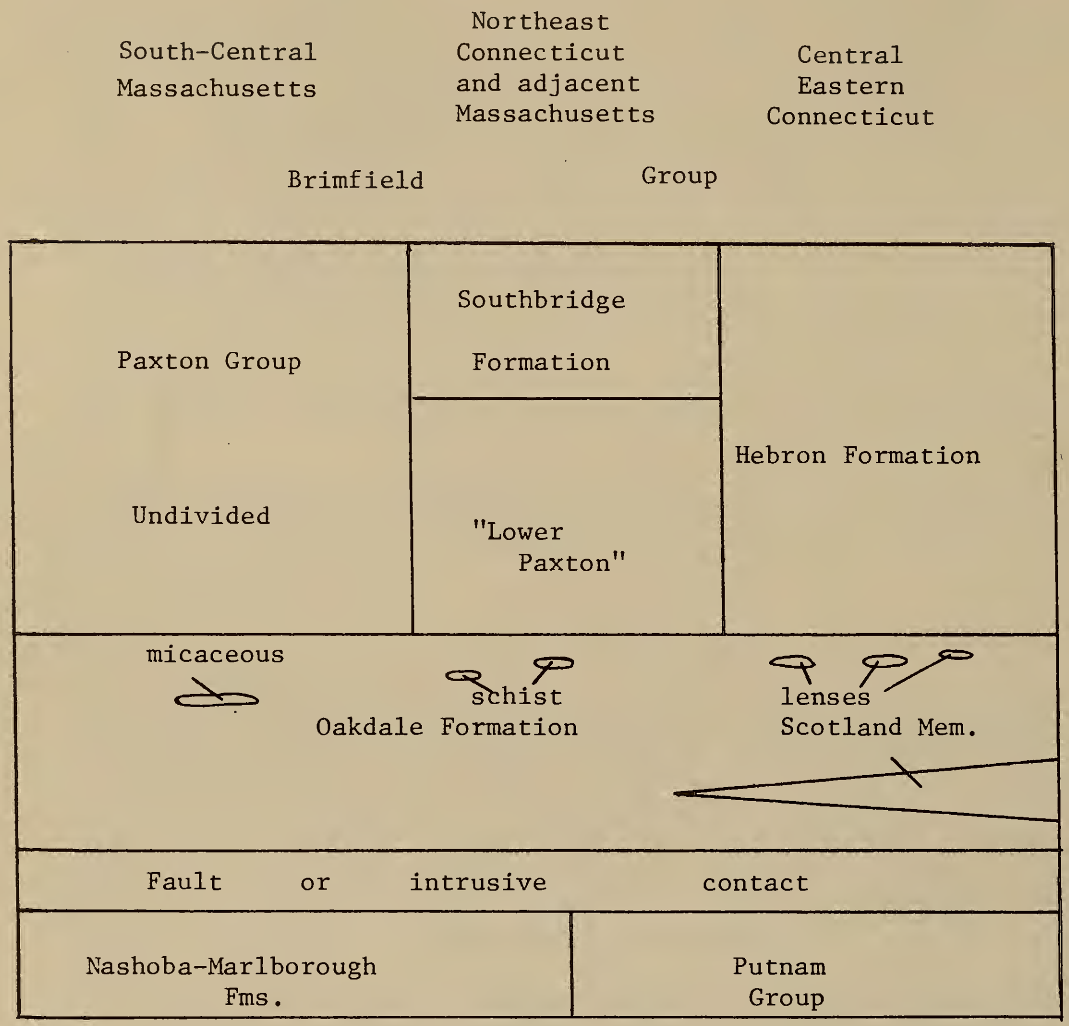

Figure 3 - Stratigraphic relations of the Paxton-Oakdale (Hebron) sequence as presently interpreted (modified from Barosh and Pease, 1981).

lower part of the Oakdale in Connecticut. The member is as much as 500 m thick at its southern end; it thins rapidly northward to less than 25m and is cut out against the Canterbury Gneiss. The schist typically is only weakly layered but strongly foliated and commonly crenulated. It is coarsely muscovitic and garnetiferous and typically contains conspicuous quartz stringers and pods. The Scotland contains successively more interlayers of metasiltstone towards the northern end of its exposure.

CONTACT RELATIONS

The contact between the Oakdale and overlying "Lower Paxton" is nearly everywhere a fault in eastern Connecticut, but in Massachusetts the contact appears to be conformable and gradational. The Oakdale is finer-grained and thinner-layered, and the rock characteristically weathers in flaky sheets rather than discrete partings parallel to layering. The schistose granulite of the overlying Paxton is in the sand size range in contrast to the silt grain size of the Oakdale.

The Oakdale is in fault and in intrusive contact with the Canterbury Gneiss and Lebanon Gabbro south of the Nightingale Brook fault along the east side of the Willimantic Dome. A narrow arcuate band of Lebanon Gabbro terminates the Oakdale to the south (Fig. 1).

AGE

No fossils have been found in the Oakdale Formation nor in any stratigraphic units associated with the Oakdale. Radiometric dates of related igneous rocks intrusive into the Oakdale and related stratigraphic units do provide possible minimum ages. An approximate age of 405 m.y. (Zartman, written commun.) has been assigned to the Canterbury Gneiss, which intrudes the Oakdale. An approximate age of 440 m.y. (Zartman, written commun.) has been assigned to the Hedgehog Hill Gneiss, which intrudes the Hamilton Reservoir Formation, part of the Brimfield Group, which lies near the top of the stratigraphic sequence at the base of which lies the Oakdale (Fig. 2). Thus the Oakdale is at least pre-Middle Devonian in age and by extrapolation pre-late Ordovician. Detrital zircons collected from the Oakdale Formation in central Massachusetts give a late Proterozoic age of 600± m.y. according to Aleinikoff (1978). Conceivably this gives a maximum possible age for the Oakdale.

STRUCTURAL IMPLICATIONS

Separation of the Paxton-Oakdale sequence from the undivided Hebron in eastern Connecticut has necessitated changes in the structural interpretations. Much of the western part of eastern Connecticut was depicted as occupying the inverted limb of a recumbent fold by earlier workers. The axis of this fold was shown to trace a sinuous path across eastern Connecticut from southwest to northeast. This structure was premised on the existence of a simple stratigraphy in which the Scotland was considered the youngest formation and to lie in the axis of the fold. Recognition that the Scotland lies in the lower part of a continuous west-topping sequence precludes such a structural hypothesis.

ACKNOWLEDGEMENTS

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ROAD LOG

Mileage		
Cumulative	Intermediate	
		<u>START</u>. Southbridge, MA. Large outcrop at intersection of Dresser Hill Rd. and Dudley Rd. at north side of bridge over Quinebaug River (off Rt. 131, 1 mile SE of circle in center of Southbridge, MA).
		<u>STOP 1</u>. (Southbridge Quad.) TYPE LOCALITY OF THE SOUTHBRIDGE FM. The Southbridge Fm. is the upper formation of the Paxton Gp. Lithologies representative of the entire Paxton Gp. can be seen in the outcrop, but most of this rock is coarser-grained than strata in the lower part of the group. In this large outcrop evenly-bedded, conspicuously parted strata dip about 40° to the west. Beds, 5-70 cm thick, consist of schistose granulite, chiefly metasandstone, with a few pelitic folia. The rock is medium- to dark-greenish-gray with a conspicuous salt and pepper granular texture; it is composed chiefly of quartz, plagioclase and biotite. A few lenticular calc-silicate-bearing granular layers are present. The alternation of coarse-, medium- and fine-grained beds in this outcrop is typical of the Southbridge. Outcrop contains numerous pods and lenses of pegmatite, as much as 1 m thick, generally parallel to bedding.
	0.0	Start road log on south side of bridge, turn left, SE, on Rt. 131. This direction is going down section. Almost the entire section of the Southbridge Fm. is well exposed along railroad cuts on opposite side of river.
1.6	1.6	Dudley town line.

Cum.	In.	
3.1	1.5	Outcrop on left, lower Paxton.
3.9	.8	Bridge of Quinebaug River, turn left, N, immediately after crossing bridge on to Mill Rd.
4.0	.1	Railroad crossing.
4.1	.1	Outcrop on left, lower Paxton.
4.6	.5	Intersection Rt. 31 and Mill Rd. Park on Mill Rd., enter woods at fire plug across Rt. 31, walk about 50 m and angle down into old railroad cut on left.
		STOP 2. (Webster Quad.) OAKDALE FM. Medium- and dark-gray weathering silicic metasiltstone. Well bedded gently NW dipping. Beds generally 1-15 cm thick and commonly laminated. Few schist beds as much as 10 cm thick are present. Muscovite-rich parting surfaces are common. Composed of quartz, plagioclase, biotite and muscovite. Lavender and green tints reflect presence of biotite and calc-silicate minerals, respectively. Possible graded-bedding suggests tops up. Bedding well expressed on weathered outcrop surfaces, but freshly broken rock generally does not show bedding features. Thin quartz lenses and stringers are common. Minor intrafolial folds brought out by differentially weathered bedding show west over east transport with sheared out limbs. No evidence of regional isoclinal folding nor of axial plane cleavage is present. A few small intrafolial thrust faults also indicate west over east transport. The exposures in this extensive cut are representative of the Oakdale Fm. both in this area and at its type area at Oakdale, MA. The rock, although very resistant in fresh exposures, is a valley former relative to the "Lower Paxton Fm." to the west, which in turn is less resistant in erosion than the Southbridge. There are few natural exposures of Oakdale. The Oakdale is characterized by a thin-bedded quartz, plagioclase, biotite metasiltstone containing minor amounts of muscovite chiefly in lamellae and rarely thin beds.
		Return to cars and turn right, S, onto Rt. 31.
5.0	.4	Entering Thompson, CT.
5.1	.1	Cross CT. Rt. 197 and continue S.
5.2	.1	Railroad crossing.
5.3	.1	Turn left, SE, on Rt. 131.
5.6	.3	Turn right, S, on Fabyan (Woodstock) Rd.
		Traveling over till-covered Oakdale, note ridge to SE formed by intrusive complex.

Cum.	In.	
6.2	.6	Bridge over Quinebaug River, turn right across river on Fabyan (Woodstock) Rd.
6.5	.3	Keep to right on Blash Rd.
6.6	.1	Abandoned gravel pit on left; rubble covered slope of gravel pit with weathered loose outcrop.

STOP 3. (Webster Quad.) PELITIC OAKDALE. Dark gray, rusty weathering schist with siltstone interbeds 1-5 cm thick. Bedding is warped and crenulated as is common where units of different competency are interbedded. The pelitic layers are muscovite-rich and the siltstone layers are similar to those at Stop 2. The pelitic intervals within the Oakdale range from lamellae to as much as 500 m thick. Mappable muscovite intervals have been mapped as Scotland Schist in Ct, and Gove in NH and Gonic in ME. The schist in this area would probably be mappable if exposures were better. Note uplands to east formed by an intrusive complex. The western part of the intrusive rock contains xenoliths of Oakdale that show no evidence of coarsening due to contact metamorphism.

Break in log for supplementary Stop 3A. Continue 1.0 miles on Blash Rd. which becomes Chandler School Rd.

Turn left, S, on Dugg Rd., and drive about 200 feet to small exposure on left side of rd.

STOP 3A. (Webster Quad.) BASAL PAXTON. Brownish medium-gray very fine-grained thin-bedded schistose granulite or metasandstone beds 1 to 5 cm and commonly laminated. Composed of quartz, plagioclase and biotite with trace of muscovite. Has salt and pepper texture. Thin more resistant calc-silicate beds also present. The rock in this exposure appears transitional between the Oakdale metasiltstone and the fine-grained metasandstone of the "lower Paxton Fm". Note flaky partings in this weathered outcrop which are a common feature of the lower Paxton.

Rock more typical of the "lower Paxton" is exposed 0.3 miles due north of here on Converse Rd., which is an extension of Dugg Hill Rd.

Return to Stop 3 and continue road log from Stop 3.

Return 100 m to intersection Fabyan Rd., and Blash Rd., turn right, S, (Woodstock Rd. becomes Paine District Rd.)

7.6	1.0	Outcrop rusty pelitic Oakdale in bushy roadcut on right.
7.7	.1	Intersection Paine Rd. and Paine District Rd. continue straight, S.

Cum.	In.	
9.5	1.8	Bear right at V.
9.7	.2	Bear left at V onto Roseland Park Rd.
11.7	2.0	South Woodstock, CT, turn left, S, on Rt. 169.
12.0	.3	Continue on Rt. 169 to right towards Pomfret, CT.
12.3	.3	Annhurst College.
14.7	2.4	Pomfret, CT, Junction of Rts. 169 and 44, continue straight, S.
16.7	2.0	Bear left on Rt. 44.
16.8	.1	Bear right on Rt. 44.
17.3	.5	Right again, W, on Rt. 44.
18.2	.9	Mashomoquet Brook State Park entrance.
19.5	1.3	Abington, CT.
20.3	0.8	Abandoned part of old Rt. 44 on left just south of present highway. A low outcrop is present near the east end of the abandoned roadway and outcrops occur in the field to the south. Also, a small exposure can be seen on the right side of the present road.
		STOP 4. (Hampton Quad.) OAKDALE FM. Very gently northwest dipping typical light-to greenish-medium-gray well-bedded metasiltstone. Beds 4 to 30 cm thick. Beds part along lamellae on weathered surfaces, muscovite-rich lamellae are sparse. Very uniform metasiltstone typical of Oakdale, possibly slightly coarser than previous stops.
		This outcrop was mapped as Scotland Schist by Dixon on the basis of the presence of muscovite. The trace amount present in these rocks, however, is characteristic of typical Oakdale and not of the muscovite schist that forms the Scotland of its type area. The Scotland Member, as it is presently restricted, is a thick muscovite schist interval that lies stratigraphically much lower in the Oakdale Fm.
		Continue W on Rt. 44.
20.8	.5	Passing Drown Rd. on left.
21.0	.2	Passing Lyon Brook, position of the northeast-trending Nightingale Brook fault.
21.8	.8	Good exposures of Canterbury (Eastford) granitic gneiss.

Cum. In.

21.9 .1 Turn left on dirt road sharply back towards E, drive 60 m and turn right, S, through gate into State forest. Note abundant float and stone fences of Canterbury Gneiss, which underlies this area.

23.6 1.7 Road enters on right, continues straight. Good exposures of Canterbury along pipeline right of way to right. Just past pipeline cross the narrow northeast-trending Catden Swamp which follows the trace of the Nightingale Brook fault.

25.1 1.5 Hampton Reservoir through trees on left. Small dirt road on left at culvert in road.

25.2 .1 3rd culvert in road after passing small dirt road. Small woods rd. on right, park and walk up woods rd. about 100 m to large outcrop (4 m high and 15 m long) to left of road.

STOP 5. (Hampton Quad.) LOWER PAXTON. Gently northwest-dipping, medium-gray schistose granulite, slightly irregularly bedded, 4-15 cm thick, strongly parted and differentially weathered. Fine-grain sand size, salt and pepper textured granulite with a few 1-4 cm thick light-green calc-silicate-bearing layers. The unevenness of the bedding may be in part due to original depositional features and concretionary nature of some calc-silicate-bearing pods, but is largely due to disruption caused by tectonic transport subparallel to bedding. Many small scale sedimentary features are still well preserved, but difficult to observe. Note the lack of muscovite lamellae and quartz lenses that are typical of the Oakdale and the greater amount of biotite than is found in the Oakdale. Pegmatite pods and stringers are present, generally subparallel to bedding, and some sills of Canterbury are present in the upper part of the outcrop.

Return to cars and continue S along gravel rd.

25.6 .4 Paved rd., turn left, E, and immediately left into abandoned railroad grade. Do not stay on paved rd. Railroad grade crosses Nightingale Brook fault which separates "lower Paxton" from Oakdale in this area.

25.9 .3 Outcrop on both sides of railroad.

STOP 6. (Hampton Quad.) TYPICAL OAKDALE IN FOOTWALL OF NIGHTINGALE BROOK FAULT. This outcrop has all the sedimentary features of the Oakdale seen in Stops 2, 3 and 4. It is a greenish medium-gray metasiltstone, commonly laminated in beds 1 to 20 cm thick interbedded with rusty weathering muscovitic schist intervals 20 cm to perhaps as much as 1 m thick. The rock is deceptively massive looking on some joint surfaces but the weathered outcrop brings out the fine sedimentary layering.

Cum.	In.	
		The contrast of pelitic and metasiltstone layers brings out an intricate pattern of chevron folds, with gently dipping axial planes, that climb nearly vertically across the outcrop. The pelitic beds also appear to be more lightly folded than adjacent metasiltstone intervals. Some slippage has occurred on the metasiltstone-pelitic contacts. The fold axes plunge about 10° to N.25° E., but are variable. The axial planes range from N.70W. to as much as N.40E. and dip 10-20° to the N. Note that the folds are bedding plane folds and there is an absence of axial plane cleavage or any evidence of transposition of bedding. The folding is related to movements in the adjacent Nightingale Brook fault and does not represent a regional fold set.
		Return to cars and continue NE on railroad grade.
26.1	.2	Turn right off railroad grade on small woods rd., drive 70 m, turn sharply left on paved rd. and drive N over bridge crossing railroad grade.
26.7	.6	Overgrown rd. on left leads to difficult to find outcrop on S side of topographic knob, about 130 m to the N, that is right on the Eastford town line. This outcrop is very similar to Stop 6, including climbing chevron fold contacts of schists and metasiltstone. This too lies adjacent to the Nightingale Brook fault.
27.1	.4	Small overgrown drive, immediately before stream crossing, leads to deserted house, outcrop of Oakdale at stream behind house. Outcrop is well laminated differentially etched metasiltstone with traces of muscovite.
27.3	.2	T. in rd. turn right, S, on Stetson (Lewis) Rd.
27.5	.2	Lewis Rd., turn right, S, on Rt. 97.
27.7	.2	Bear left at bend in Rt. 97 onto Bigelow Rd.
28.2	.5	Rd. enters on left, continue straight.
28.4	.2	Outcrop on left of the northern end of the Scotland member of the Oakdale is beginning of numerous exposures over the next 800 m.
28.5	.1	Continue to north end of wooden fenced paddock on right, park, cross street and climb 40 m uphill to east to large outcrop.
		STOP 7. (Hampton Quad.) SCOTLAND MEMBER. Gently dipping unevenly bedded light-to medium-gray, with silvery sheen, crinkled muscovite schist, fine garnet and staurolite ubiquitous, contains interlayers and crinkled lamellae of metasiltstone. This northern part of the Scotland Member is thinner and generally

Cum.	In.	
		contains more siltstone layers than farther south. Pegmatite pods and stringers present.
		Proceed S scross small fault controlled gully at altitude of top of outcrop to next outcrop. Fault has brought up the underlying Oakdale metasiltstone so that the top of the outcrop is about at the contact with the basal Scotland. The contact appears to be conformable and gradational with interlayering of the two rock types. Proceed across power line right of way along the top of outcrop and drop down face of outcrop just S of power line.
		The Oakdale here has calc-silicate-bearing layers rhythmically interbedded with metasiltstone beds.
		Continue downhill past power station to rd. and return to cars.
		Continue S along N. Bigelow Rd.
29.7	1.4	Cross old Rt. 6.
30.7	.8	Intersection Rt. 6, turn right, W.
30.8	.1	Outcrop on right, Oakdale metasiltstone with calc-silicate-bearing beds. Tightly oppressed, nearly flat lying folds are prominant in this outcrop. Scotland member is exposed in woods above. The character of the folding suggests the contact may be tectonic here.
31.1	.3	Turn left, S, on Rt. 97. Cross bridge right after turn. Oakdale metasiltstone exposed in stream below.
34.6	3.5	Cross Brooklyn Turnpike.
37.0	2.4	Intersection Rt. 97 and 14. Turn right, W.
37.6	.6	Scotland, CT, turn left, S, on Rt. 97.
38.6	1.0	Bear left at cemetery on Rt. 97.
39.0	.4	Good outcrop of Scotland just back of rd. intersection on left.
39.7	.7	Crossing Waldo Brook, outcrop of Oakdale metasiltstone in stream bed to right.
41.2	1.5	Turn right, W, at sign to Brookside greenhouse (Jerusalem Rd.).
41.3	.1	Hills in foreground underlain by Scotland.
41.6	.3	Crossing bridge at base of Scotland, numerous outcrops of

Cum.	In.	
		Scotland along right, N, side of rd. next half mile.
42.2	.6	Small turnout on right side, park and walk through gate down to power house on river. Outcrops along railroad track on both sides power house (if cannot get into power station, visit outcrop uphill from turnout).
		<u>STOP 8</u>. (Scotland Quad.) SCOTLAND MEMBER. Massive contorted schist, bedding difficult to see, except where metasiltstone interlayered with schist. Reddish-brown-weathering muscovite schist with garnet and staurolite. Note quartzite bed about 20 cm thick in schist SE of power house. Some pulled apart beds of calc-silicate-bearing metasiltstone are present. Crinkled surfaces form very irregular lineations 0-20° S.30W. These represent the general plunge of axes of oppressed folds. Pods of pegmatite and vein quartz are present.
		Return to cars and continue NW along Jerusalem Rd.
43.0	.8	Pass Myers Rd. on right.
43.6	.6	Pass Weldon Drive. Outcrop of Oakdale stratigraphically above Scotland on railroad cut directly S below end of Weldon Drive, about 500 m from Jerusalem Rd.
45.6	2.0	End of Jerusalem Rd. at Rt. 203 turn left, S.
46.3	.7	Crossing Shetucket River after railroad.
46.5	.2	Intersection Rt. 32, continue straight, S, on Main St. through S. Windham, CT, and up hill.
46.8	.3	Continue straight passing Sanitorium Rd., fault showing granulated Lebanon Gabbro is exposed about 100 m to right on road.
46.9	.1	Bear right at fork in rd.
48.9	2.0	Intersection Kick Hill Rd. and Chappel Rd. near crest of Kick Hill. Scattered outcrops of mostly schist and metasiltstone occur in this vicinity. These are assigned to the Oakdale rather than Brimfield and Hebron as previously mapped by Snyder.
49.9	1.0	Intersection Kick Hill Rd. and Rt. 207, turn left, NE.
50.1	.2	Entrance to field on right just before stream crossing, park. Scattered low outcrops on brow of hill to S, crossed by power lines.
		<u>STOP 9</u>. (Willimantic Quad.) UPPER PART OF OAKDALE FM. Thin, slightly irregularly-bedded, medium-greenish-gray thin-bedded

Cum. In.

metasiltstone, dipping gently northwest. Muscovite lamellae and beds as much as several cm thick form less than 10 percent of rock. These commonly impart a silvery sheen to bedding surfaces. These exposures are quite unlike the Scotland at the type locality with which they were originally correlated.

Return to cars. End of guided trip. Two additional stops are described below for those with time. The first is along the quickest route to Kingston, R.I.

Turn around, proceed S on Rt. 203.

50.3 .2 Passing Kick Hill Rd.

51.3 1.0 Lebanon, CT, turn left, E, on Rt. 87.

56.3 5.0 Exposures on both sides of rd.

STOP 10. (Fitchville Quad.) LOWER OAKDALE - SCOTLAND MEMBER CONTACT. This stop shows features almost identical to those at Stop 7 (Hampton Quad.). Well bedded and thinly layered Oakdale metasiltstone with prominant calc-silicate-bearing layers underlies rusty weathering muscovite schist. The contact is conformable and gradational. The rusty weathering schist at east edge of outcrop, however, is probably a repetition due to faulting.

57.9 1.6 Intersection Rt.32, turn right, S, exposures of Canterbury Gneiss.

58.5 .6 Intersection Rt. 32 and Rt. 2.

To see exposures of the Hebron Formation unlike the Oakdale Fm. and more similar to the Southbridge, take Rt. 2 west to exposures along highway about 1 mile beyond Gilman, CT, (Exit 22). To go directly to Kingston, R.I. take Rt. 2 east and follow instructions below Stop 11.

STOP 11. (Fitchville Quad.) HEBRON. These roadcuts consist of gray to greenish-gray medium-grained calc-silicate-bearing biotite schistose granulite in thin to medium slightly uneven beds. The bedding is nearly horizontal with numerous low angle recumbent folds showing NW over SE sense of transport. Very strong penetration axial plane lineation trends approximately 10^{o} N.15W. The numerous small low angle thrust faults show the same sense of transport. These outcrops lie in the footwall of a very low angle thrust fault that is eroded here, but exposed to the W where Bigelow Brook Fm is in the upper plate, that forms the Colchester nappe.

To proceed to the Univ. of R.I., Kingston, R.I., take Rt. 2 east to Rt. 52, north on Rt. 52 to Rt. 138 exit (exit to Pachaug, alternate route to R.I. beaches) and east on Rt. 138 to Kingston.

Pleistocene Geology of Block Island

by

Les Sirkin
Adelphi University

Abstract

The cliffs and surface features of Block Island offer us a unique opportunity to study Late Pleistocene glacial deposition and tectonism, as well as late-glacial recession of the continental ice sheet.

Introduction

Block Island lies about 20 km south of the Rhode Island coast and a similar distance east of Montauk Point, Long Island. In the classical correlation of end moraines in southern New England, Block Island is only a stepping stone between the Vineyard Moraine of Martha's Vineyard and the Ronkonkoma Moraine of Long Island (Flint and others, 1959). Recent studies show that this linear correlation is at best an oversimplification (Sirkin, 1976, 1981). The presence of two superposed drift sheets, with evidence of at least two glaciations and deposition from two glacial lobes, as well as recessional moraines and associated deposits attest to a more complicated glacial history than was previously envisioned (Sirkin, 1981). It is also apparent that both glaciations occurred during the Wisconsinan Glacial Stage of the Pleistocene (Fig. 1).

Geomorphology

Block Island has been formed from two relict morainal segments that now stand as highlands rising from the sea. The highlands are tied together by beach deposits in the form of a double tombolo. Coastal erosion has cut impressive cliffs into the moraines. These exposures offer a unique opportunity for us to study in cross section the glacial deposits and the evidence of glacial tectonics in both dip and strike directions and to directly relate structures, deposits and topography to glaciations. Surface features in both segments of the Island include the moraines, meltwater channels and the distinctive morainal topography. A cluster of north-northwest to south-southeast trending drumlins nearly encloses an embayment with a similar trend in the central area.

A large pond at the north end of the Island is bordered north and west by partially stabilized dunes and beach deposits. A north trending spit juts from the north end of the Island and can be traced for nearly 2 km toward the Rhode Island coast. A line of coastal dunes lies parallel to the eastern tombolo, which is supported, in turn, by glacial sediments. Erratics are scattered across the Island and lag bolder concentrations armor the outer beaches as well as those of the ponds. Multiple gravel berms up to one meter above sea level indicate seasonal and storm high water. These berms are often shaped in beach cusps.

Stratigraphy

The glacial deposits of Block Island overlie Late Cretaceous sand and clay

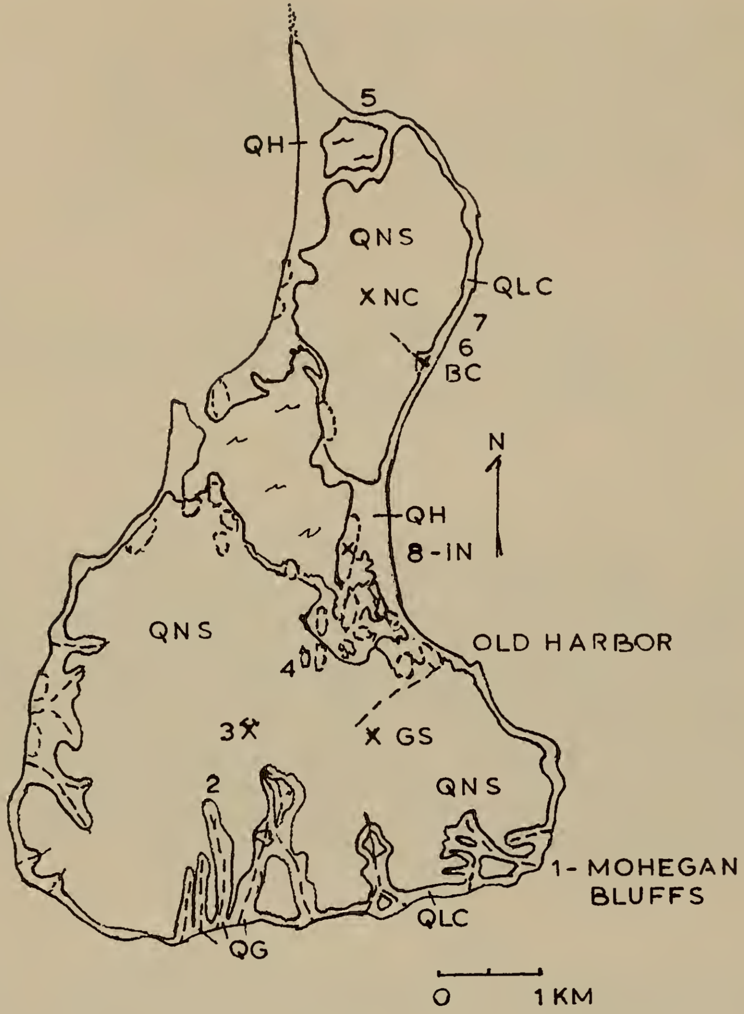

Figure 1. Surficial geology of Block Island. (Profile of NE Bluffs sketched in Fig. 2).

Rock Units

QH - Holocene deposits
QG - Meltwater channel gravel
QNS - New Shoreham Formation (Woodfordian)
QLC - Lighthouse Cove Formation (Altonian)
KR - Raritan Formation

Landforms

◌ Drumlins
--- Meltwater channels
x Pollen sites
1,2.. Field trip stops

Figure 2. Sketched profile of the northeast cliffs. Sketch in the Geology.

with lignitic seams (Fig. 1). The lignites contain a microflora that represents Cretaceous pollen zone V, and thus they occur in strata that are equivalent to the South Amboy Fire Clay and related deposits in Long Island and New Jersey (Sirkin, 1974). Seismic refraction has shown that up to 41 m of Cretaceous strata underlie Block Island (Tuttle, 1961). Masses of Cretaceous sediment are redeposited in the Late Pleistocene moraines.

At this writing no Early Pleistocene glacial or interglacial deposits have been identified in Block Island. The glacial drift of the Island is believed to be entirely Wisconsinan in age; it may be separated into two sequences of Early Wisconsinan or Altonian and Late Wisconsinan or Woodfordian age (Sirkin, 1976, 1981) (Table 1).

Altonian

The lower drift sheet is exposed in the sea cliff sections of the Island. The best section occurs in the Mohegan Bluffs in the southeast. Here the Altonian deposits are structurally and lithologically complex, but they may be divided into three units. The lowest is a dark gray or olive gray till (5Y4/1) that contains about 65 percent dark-colored till stones, has a northeasterly till fabric, and is crudely stratified. The middle unit consists of tightly folded, rhythmically bedded clay and silt layers and thin lenses of yellowish brown till (10YR5/4) and gravel. These are overlain by olive gray till (5Y4/1) that resembles the lower till of this section. Kaye (1960) proposed that the section developed through ablation processes coupled with ice movements, both recession and readvance. North of Mohegan Bluffs the Altonian drift grades into a single till unit about 3.0 m thick that overlies outwash.

Kaye's suggested ablation mechanism for the Mohegan Bluffs section appears plausible. The thrusts and folds in the drift are undoubtedly due to glacial tectonism and show agreement in the southerly trend of deformational axes. The Altonian ice was also active in redepositing masses of Cretaceous and Altonian sediment. The tightly folded rhythmites, for example, are probably proglacial lake beds that were deformed and incorporated in the drift. Woodfordian glacial tectonics have complicated the Altonian section by lifting and thrusting large blocks of till. Sand and gravel from the Woodfordian ice sluiced into the openings and engulfed the Altonian clasts.

The northeasterly till fabrics and the large proportion of till stones derived from strata in the Narragansett Embayment in the Altonian till indicate that deposition came from a glacial lobe that crossed the Narragansett lowland. The Altonian till section in the Mohegan Bluffs of Block Island is similar to the corresponding section at Montauk Point, which contains the Montauk Till. This apparent correlation was used by Sirkin (1976) who referred the Early Wisconsinan deposits of Block Island to the Montauk Drift. However, due to the physical separation of these sections and the recognition of an outwash unit beneath the till, the two sections may be differentiated. Thus, the Altonian till in Block Island has been designated the Mohegan Bluffs Till and the underlying outwash is named the Old Harbor Sand. Both the till and outwash are members of the Lighthouse Cove Formation (Table 1).

The Altonian moraine of Block Island, recognized in the topographic high of the deposits at Mohegan Bluffs, is probably not the end moraine of the Altonian glaciation (Fig. 3A). The Altonian ice appears to have advanced

Stage	Substage	Rock Units	Age, Yr BP
WISCONSINAN	Woodfordian	New Shoreham Formation Old Town Till Issacs Corner Sand	-20,000 -21,750
	Farmdalian	(Represented in Long Island)	-28,000
	Portwashingtonian		-33,000
	Nassauan	(Inferred in L.I.)	>43,000
	Altonian	Lighthouse Cove Fm. Mohegan Bluffs Till Old Harbor Point Sand	

Table 1. Wisconsinan stratigraphy in Block Island.

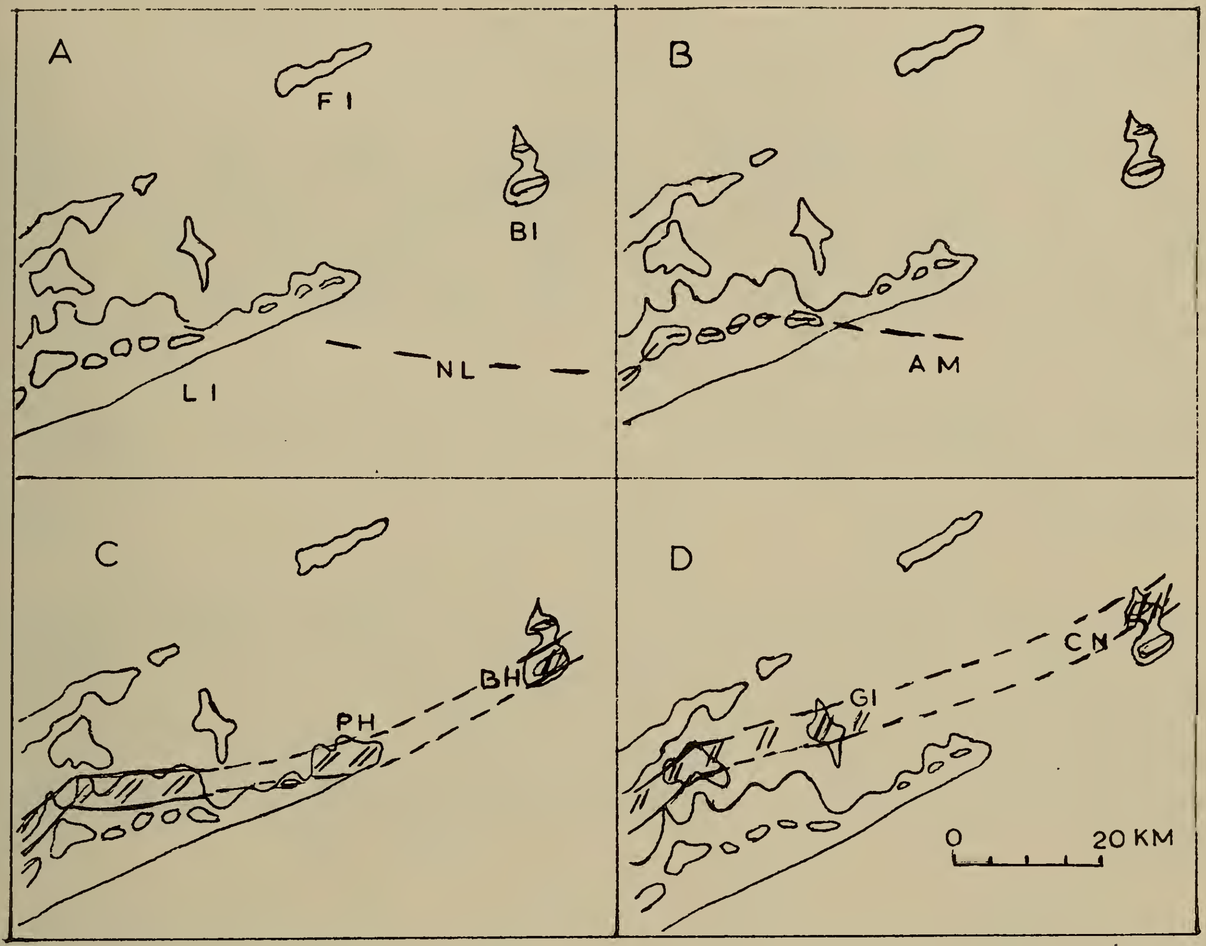

Figure 3. Correlation of drift and morainal envelopes, Block Island to eastern Long Island. A) Altonian: position of end moraine of the Narragansett Lobe (NL) is believed to be well south of Block Island and Montauk Point. B) Woodfordian end moraine: the Amagansett Moraine (AM): its counterpart would lie south of Block Island. C) Recessional morainal envelope: the Prospect Hill Moraine (PH) of Long Island, Beacon Hill Moraine (BH) of Block Island. D) Recessional morainal envelope: the Gardiners Island Moraine (GI), Corn Neck Moraine (CN) of Block Island.

beyond the southern margin of the Island based on the presence of submerged erratics.

Mid-Wisconsinan

Evidence of mid-Wisconsinan deposition has not yet been found in Block Island. In at least two areas of the Island, silty alluvium occurs between the upper and lower drift sheets. However, no dateable or fossiliferous sediments have been found. Although a marine unit of pre-Woodfordian age may exist in the subsurface based on the occurrence of shell fragments in well cuttings, as reported by water well drillers. The possibility exists, therefore, that an interstadial or interglacial interval, a Sangamonian or Portwashingtonian equivalent, for example, might be found in the subsurface. Both alluvium and shell-bearing strata could exist as ice-shoved and redeposited masses of sediment in the drift. Such clasts can eventually be exposed in the erosion of the cliffs, but they are also worn away.

Woodfordian

The Woodfordian glaciation advanced to its terminal position around 21,750 years ago (Sirkin and Stuckenrath, 1980). The upper or Woodfordian drift sheet in Block Island is now referred to as the New Shoreham Formation. It consists of up to 16.7 m of outwash, named the Isaacs Corner Sand, overlain by as much as 3.4 m of yellowish-brown till (10YR5/4), the Old Town Till (Sirkin, 1981). The outwash is mainly cross-stratified sand and gravel that in places is cemented with iron oxides due to ground water piping. The contrast between the light-colored outwash and the darker Altonian sediments is quite apparent in the cliff sections. In northeastern Block Island a 13.3 m thick sequence of east-dipping sand beds may represent a delta.

In central Block Island, the cliffs contain up to 10 m of ice-contact rubble and outwash. Much of this material has been folded and thrusted by the Woodfordian ice. The outwash and related deposits are generally overlain by till. Till fabrics have a north-northwest to south-southeast preferred orientation (Sirkin, 1976). About 34 percent of the till stones are granites rich in K-feldspars. The fabric and rock type indicate a source in the granites of southeastern Connecticut and southern Rhode Island, and therefore, deposition from an Eastern Connecticut-Western Rhode Island Lobe of the glacier.

Moraines

The New Shoreham Formation mantles the Lighthouse Cove Formation throughout most of the Island. As discussed, the lower drift forms conspicuous high areas that may be relicts of Altonian moraines, so that the Mohegan Bluffs section incorporates a recessional moraine of Altonian age, draped over by ground moraine deposits of Woodfordian age. This Woodfordian drift is included in the envelope of the Beacon Hill Moraine in the absence of a Woodfordian end moraine south of Mohegan Bluffs (Fig. 3B and 3C). The Beacon Hill Moraine, which forms a prominent ridge across the southern half of the Island, marks the crest of the recessional envelope of the Eastern Connecticut-Western Rhode Island Lobe in southern Block Island and is the eastward continuation of the Prospect Hill Moraine of the Montauk Peninsula (Sirkin, 1981).

Deformation

The advancing Woodfordian glacier incorporated masses of pre-existing sediments into its bed load. Cretaceous and Altonian strata were ice-shoved and engulfed in the Woodfordian Isaacs Corner Sand. This outwash was also folded and thrusted. Because the ice rode on the outwash, the overlying till appears to truncate the sand with an angular unconformity, even though these deposits were derived from the same glacier. Thrusts occur on the Altonian drift occasionally with Cretaceous clay in the sole of the fault. High angle faults that cut through both drift sheets may be the result of collapse, resulting from melting of residual ice. The structural sense of the various expressions of deformation agrees with the direction of ice movement.

Woodfordian Recession

Meltwater from the ice at the Beacon Hill stand cut deep channels into the glacial deposits. In front of the ice lay small recessional deposits, kames. Now, erratics dot the surface and the shallows nearshore, and outwash gravels partially fill the channels, turning some of the valleys into elongate lakes.

A drumlin field occupies the central portion of the Island and gives the impression that a minor stand of the glacier was at some time overridden by a readvance. The drumlins exhibit both erosional and depositional features and are overlain by till and loess. The drumlin at Indian Head Neck is an erosional form, carved in a sequence of varve-like clay, silt, and fine sand rhythmites, with till and loess at the top. The nearly-horizontal beds are offset by high-angle faults that dip southward, due to ice shove or collapse. The rhythmite section probably represents proglacial lake deposition, with about 100 sets of beds preserved.

The drumlins and proglacial lake might have been formed during the advance of the Woodfordian glacier, or they may be the result of recession and minor readvance during deglaciation. Judging from the style and intensity of deformation associated with the main advance of the Woodfordian glacier as compared with the minor, ice-shove and collapse features and the size of the drumlins, fluctuation of the receding ice front seems a more likely mechanism in this case.

This readvance may also have enhanced the form of the depression in central Block Island that has become the Great Salt Pond. Embayments with this northwest-southeast orientation are also common in Long Island, for example, in the Montauk Peninsula where similar embayments are cut into an equally similar morainal setting. The Sandy Hill kame on the west side may also have been deposited as the ice receded from the Beacon Hill Moraine, or this deposit may have formed during the minor readvance. Kames also occur in similar positions with respect to embayments in western Long Island (Sirkin, 1981).

The ice receded to the position of the Corn Neck Moraine which forms an east-west ridge across northern Block Island and creates the hummocky topography of the northern portion of the Island. This moraine has its apparent western counterpart in the Shelter Island-Gardiners Island Moraine of Long Island (Fig. 3D). The deltaic sediments of the northeast coast of the Island may have been deposited during or just after this stand as the ice withdrew from the Block Island position.

In viewing the distribution of modern landforms, no additional moraines or islands appear in Block Island Sound between the Corn Neck morainal envelope and the Charlestown Moraine on the mainland Rhode Island coast. Perhaps glacial debris exists in the subsurface sediment of the Sound, but only lacustrine sediment, representing deposition in a proglacial lake dammed between the end moraines and the mainland ice, is reported (Bertoni and others, 1977). In any case, a fairly thick loess blanket covers Block Island, particularly in the north, where up to 1.5 m of silt have been observed. Periglacial phenomena, such as solifluction, have also been seen in cellar excavations.

Pollen Stratigraphy and Environments

The oldest Pleistocene pollen data for Block Island are derived from the rhythmites in the Indian Head Neck Section, as reported by Sirkin (1976). A few specimens of pine, birch, willow, alder, sedge, grass, Polygonum, Dryas (?) pollen in these sediments suggest that tundra existed in Block Island even as the ice receded to the Corn Neck position. Thus, a Late Woodfordian herb pollen zone with an age in the 20,000 yr B.P. range (a median age for the Woodfordian glaciation) may be inferred for Block Island. The late- and postglacial pollen record has been obtained from bog core samples. The sites, one in the southern morainal envelope and one in the north, have yielded a pollen zonation comparable to that of southern New England and southern New York. The record begins with the late-glacial herb pollen zone which is interpreted from pollen spectra in the basal sediments of the southern bog, the Great Swamp. The spruce, pine, and oak pollen zones are found consecutively in both sections (Sirkin, 1976).

While the age of the rhythmites and of the basal Great Swamp sediments can only be approximated, a radiocarbon-dated pollen record has been obtained from a peat bog exposed in section by erosion along the northeast coast. The pollen record contains at the base, herb pollen zone spectra characteristic initiall of a shrub tundra and then succeeded by a park tundra sequence (James Cotter, personal communication, 1979). Spruce, pine, and oak zone spectra follow the herb zone. A sample from the upper part of the spruce zone has an age of 11,900 ± 100 yr B.P. (W-4312, Meyer Rubin, personal communication, 1979).

Summary

The Pleistocene history of Block Island is interpreted from evidence that includes two drift sheets, moraines and surface features. The older drift which is placed in the Altonian Glacial Substage of the Wisconsinan Stage, was apparently deposited by the Narragansett Lobe of the glacier. During the Woodfordian Substage, the younger glacial lobe came from a more north-northwesterly direction. Both ice sheets formed end moraines and recessional moraines in the vicinity of Block Island. Two recessional morainal envelopes separated by a zone of glacial fluctuation form the Island's dominant topography. Excellent sea cliff exposures reveal the superposition of the Altonian and Woodfordian glacial sediments and the structural complexities of glacial tectonics. The Island was probably deglaciated and ice free in mid-Woodfordian time, around 20,000 years ago. A loess blanket of varying thickness mantles the glacial deposits. The record of vegetation begins with tundra, which was probably established during deglaciation. Spruce, pine, and oak forests succeeded the tundra. Postglacial geologic processes have modified the Island's topography, especially in the coastal zone.

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Itinerary

The field trip to Block Island will leave from the State Ferry Dock at Point Judith, Rhode Island. The ferry trip to Block Island takes about 1-1/2 hours. As we approach Block Island, and the northeast cliffs come into view, sketch in the geology, as you see it, on the sketched topographic profile (Fig. 2).

Distance (In Miles)		Route and Stops
Point to Point	Total	
0	0	Arrive at Old Harbor, Block Island, ferry landing. Board bus. Leave parking lot, turn south on Water Street, proceed counterclockwise 180° around the glorietta, a statue of the temperance symbol, Rebecca. Follow Spring Street southward. Pass the Spring House Hotel on west side, note pond on the east side. Spring fed pond sits on a bench on Cretaceous lignite and clay. Follow Spring Street into Southeast Light Road. The road ascends the morainal surface- scenic hummocky topography with cottages on hilltops- as it crosses the Beacon Hill morainal envelope. Pass the Southeast Lighthouse.
1.9	1.9	Stop 1. Mohegan Bluffs. The trail down the cliffs to the beach cuts across the Woodfordian New Shoreham Formation (till and outwash) and the Altonian Mohegan Bluffs Till section. From the beach the complex stratigraphic and structural relationships can be discussed. Note the sense of deformational axes, color differences between and within the drift sheets, infilling around Altonian clasts by Woodfordian sediments, the probable contact between the drift sheets, and the variety of till stone and erratic rock types. Return to bus.
1.2	3.1	Proceed westward on Mohegan Trail to Lakeside Road.
1.2	4.3	North on Lakeside Road. Pass Fresh Pond, a lake in a meltwater channel, probably dammed by outwash gravel, on the west side of the road. Turn west on Cherry Hill Road.
0.8	5.1	Stop 2. Rodman's Hollow. This is a south trending meltwater channel. The channel is over-deepened in the near distance, plugged with gravel at the southern end at Tom's Point. Small hills adjacent to channel are probably kames. Trace the channel northward on the distal slope of the Beacon Hill Moraine. Return east on Cherry Hill Road

		to Center Road. North on Center Road to gravel pit.
1.0	6.1	Stop 3. Block Island Gravel Pit. The excavation is mainly in the New Shoreham Formation (Old Town Till, Isaacs Corner Sand). Occasionally, masses of Altonian sediments are seen in the core of the excavations. Note soil profile developed on loess over till.
0.8	6.9	Proceed on Center Road northward to Beach Avenue. Take Beach Avenue east to Harbor Road intersection.
0.4	7.3	Stop(s) 4. Scenic views at this stop of the drumlin field, with cottages and homes on the hilltops. Look southward at the proximal slope of the Beacon Hill Moraine. Note DOE windmill southeast of the corner of Beach Ave. and Ocean Ave. Great Salt Pond and New Harbor are north of this intersection.
0.8	8.1	Continue east on Beach Road. Turn north on Corn Neck Road. Follow Corn Neck Road northward. The road follows the tombolo and then crosses the envelope of the Corn Neck Moraine. Great Salt Pond lies to the west of Corn Neck Road.
4.4	12.5	Stop 5. Settler's Rock. A monument to the Island's colonists of 1661. Note dune field to the north and west; spit prograding northward beyond the North Lighthouse; Rhode Island mainland to the north. Look southward toward the proximal slope of the Corn Neck Moraine.
2.0	14.5	Return southward on Corn Neck Road to Crescent Beach Road.
0.5	15.0	Crescent Beach Road east to Mansion foundation.
0.5	15.5	Walk to Ball's Cove along beach below northeast cliffs. Stop 6. Wave cut late-glacial bog. Ball's Cove. Stop 7. Ball's Cove-Ball's Point. Sea cliff exposure. Note New Shoreham Formation over Lighthouse Cove Formation (check your sketches). Note south dipping thrust on Cretaceous clay; "Pots and Kettles", outwash gravel cemented by groundwater piping.
0.5	16.0	Return to Mansion.

0.5	16.5	Return to Corn Neck Road.
		Follow Corn Neck Road south to Indian Head Neck.
1.2	17.7	<u>Stop 8</u>. Indian Head Neck Rhythmites. Very fragile section. Do not dig. Note view of Harbor, moraines to north and south.
		Return to Corn Neck Road. Turn South. Turn east on Dodge Street at intersection. Turn south on Water Street and east at entrance to ferry parking lot.
1.8	19.5	End of trip. Ferry to Point Judith.

THE DIAGENETIC TO METAMORPHIC TRANSITION IN THE NARRAGANSETT AND NORFOLK BASINS, MASSACHUSETTS AND RHODE ISLAND

by

J. Christopher Hepburn[1] and Judith Rehmer[2]

[1]Department of Geology and Geophysics, Boston
College, Chestnut Hill, Mass. 02167

[2]Waban Geoscience, Newton, Mass. 02168

Purpose

The Narragansett-Norfolk Basin Complex records the best example of Alleghenian metamorphism in New England and includes a complete sequence of metamorphic zones from unmetamorphosed sediments to the amphibolite facies (sillimanite zone). Today we will observe the changes that occur in argillaceous and arenaceous rocks at the lower end of this sequence as we proceed generally upgrade. Using metamorphic subzones determined on the basis of illite crystallinity as a guide, we will traverse from the zone of diagenesis through incipient metamorphism into the lower greenschist facies. Illite-muscovite, chlorite, quartz and feldspar dominate the mineralogical suite at these metamorphic grades. Thus, most of the mineralogical changes that occur (i.e., the improvement of mica crystallinity and magnesium enrichment of chlorites) are not visually discernable. We will, however, be able to observe the other changes that take place during incipient metamorphism such as the transition shale-slate-phyllite in argillaceous rocks, and changes in cleavage development and structural style with different lithologies. Characteristic minerals of low-grade metamorphism will be able to be seen at some stops.

Introduction

The Narragansett and Norfolk Basins (Figure 1) are erosional remnants of a late orogenic, structural and topographic depression. The basin complex contains Late Pennsylvanian non-marine clastic sedimentary rocks in association with penecontemporaneous volcanics and granitic intrusions. The thickest and most extensive unit in the Narragansett Basin is the Rhode Island Formation, mostly made up of gray and black fluvial sandstones and argillaceous rocks with minor conglomerate. These rocks grade into red-colored fluvial sediments, the Wamsutta Formation, in the northern part of the Narragansett Basin and in the Norfolk Basin. Well-preserved plant fossils are widespread in both these units and establish their partial temporal equivalence. Coal has been mined in the Rhode Island Formation intermittently from 1736 to 1959. The current energy situation has restimulated an interest in the basin and in evaluating the economic potential of the coals.

Prior to our work on illite crystallinity, sub-biotite zone rocks, which occupy approximately 2/3 of the basin complex, have been subject to little further subdivision. Quinn and Moore (1968) broadly separated this region into a chlorite zone and a zone of still lower grade rocks ("firmly indurated but essentially not metamorphosed") in the northwest part of the basin. In the southern part of the basin and along the basin margins, the metamorphic grade increases rapidly over short distances and reaches a maximum (upper amphibolite facies; sillimanite

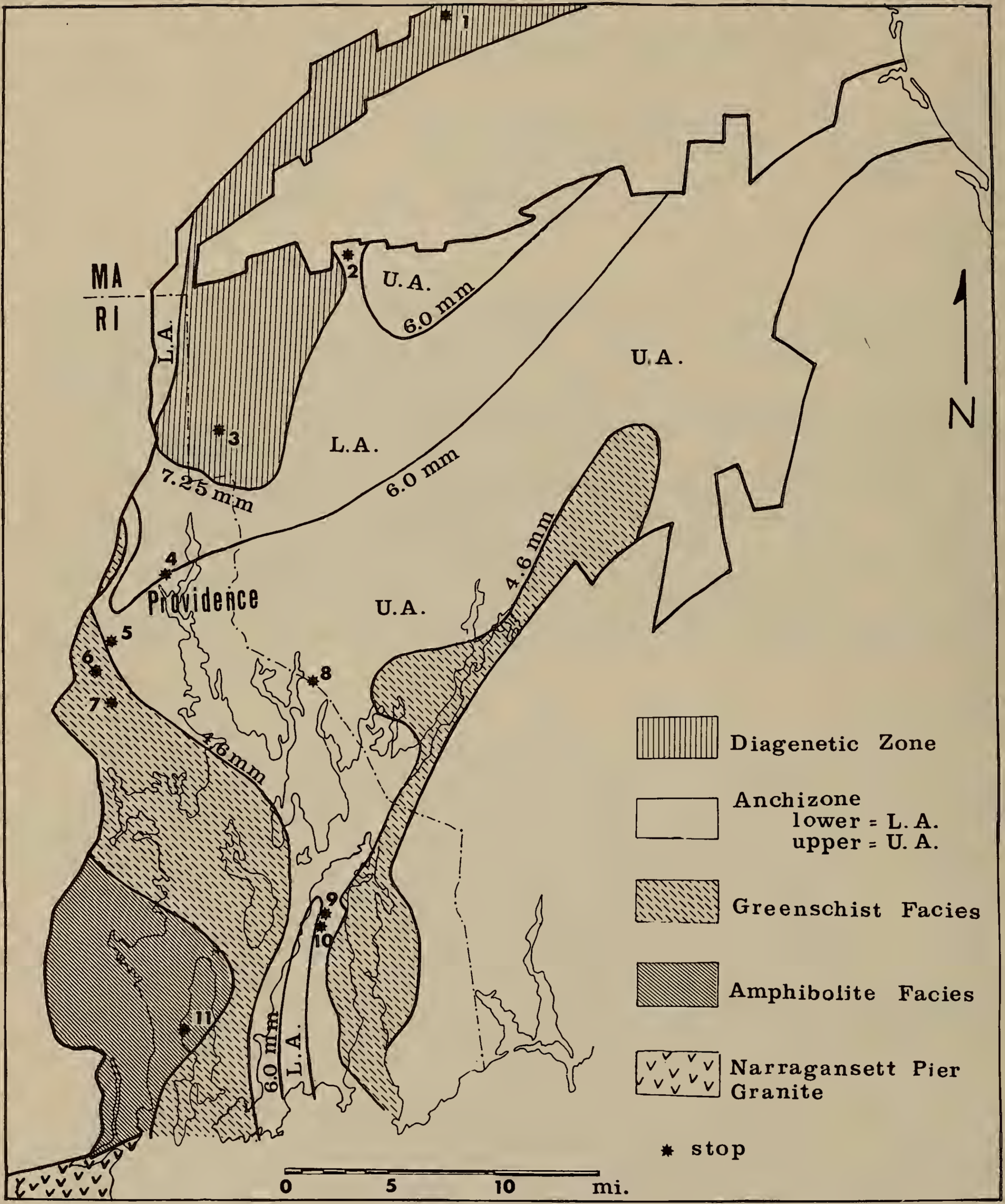

Figure 1. Map of illite isocrystallinity contours and metamorphic facies of the Narragansett-Norfolk Basin Complex, Mass. and R.I. Amphibolite facies boundary from Quinn (1971).

zone) in the southwest corner of the basin, near the Narragansett Pier Granite (Figure 1).

In the past coal from the Narragansett Basin has been variously ranked as anthracite and meta-anthracite, with somewhat ambiguous and conflicting results (Ashley, 1915; Toengas and others, 1948; Quinn and Glass, 1958; Grew, 1974). Most of the coals on which there is useful chemical data come from the areas of low-grade, sub-biotite zone rocks that comprise the bulk of the basin. According to most recent compilations, these have an apparent rank of anthracite with minor amounts of semi-anthracite and meta-anthracite (Lyons and Chase, 1979; Skehan and others, 1979). However, petrographic analysis shows that the Narragansett Basin coals have undergone a very complex thermal and structural history that can explain many of the previously confusing chemical and physical analyses of the coal (Gray and others, 1978; Raben and Gray, 1979). As a result of these studies, only the coals in the northwest corner of the basin may be considered normal anthracites. The bulk of the coal deposits of the Narragansett Basin are primarily the products of thermal alteration and coking of coals that were already at least of bituminous rank prior to coking.

Illite Crystallinity, Coal Rank and Metamorphic Mineralization

We have applied illite crystallinity techniques and measurements to the sub-biotite portions of the basin complex in an effort to refine the subdivision of this zone and to better understand the thermal history of the coals. In diagenesis and incipient metamorphism (anchimetamorphism), the 10 Å clay mineral illite gradually alters to muscovite through minor chemical and structural changes. In this process, the crystal structure becomes more regular, as 14 Å and 17 Å layers interstratified within the 10 Å illite crystal structure are lost with increases in temperature. This change is reflected in the shape of the 10 Å (001) basal X-ray diffraction peak, which becomes both sharper and more symmetrical as the grade increases and as illite becomes muscovite (Figure 2). A common measure of this change is the Kubler Index (K.I.), which records the peak width at half-height and gives particularly sensitive results in the range of high-grade diagenesis to low-grade metamorphism. Kubler (1964) by comparison of his data to other metamorphic effects has established standard ranges of illite crystallinity

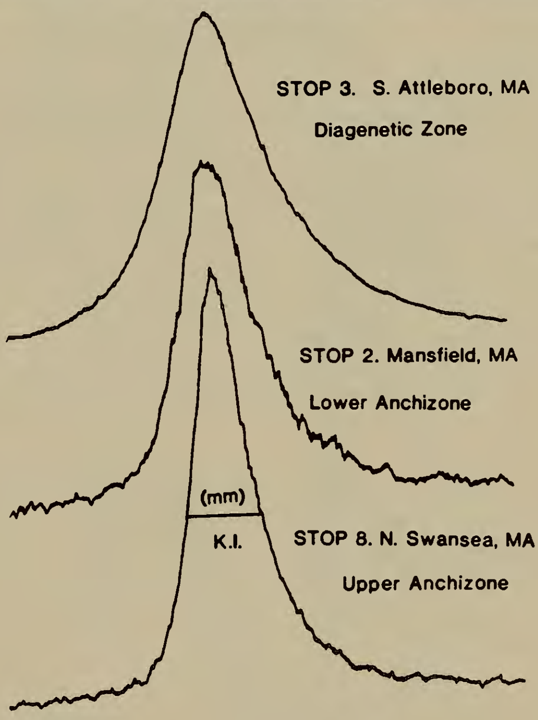

Figure 2. From top to bottom, 10 Å mica peaks becoming sharper and more symmetrical with increasing metamorphic grade. The crystallinity is measured as the peak width at half-height (Kubler index or K.I.) in millimeters.

for the zone of diagenesis, the zone of anchimetamorphism (anchizone), and the onset of the greenschist facies of regional metamorphism. The absolute values of peak width measurements are dependent upon the experimental X-ray diffraction conditions (e.g., widths of the divergence, scatter and receiving slits used; time constants; kind of radiation used; instrument differences). Thus, the use of standards that have been matched to Kubler's standards is required to define these three zones in a like manner. For Kubler's standards and conditions used in the Narragansett Basin study these values are:

Diagenetic zone = peak width greater than 7.25 mm (= Kubler's 7.5)
Anchizone = peak width between 7.25 mm and 4.6 mm
Sub-biotite greenschist facies = peak width less than 4.6 mm (= Kubler's 4.0)

We further separated out an upper and lower anchizone, with a boundary at 6.0 mm. Illite peak widths less than 6.0 mm correspond approximately with the place at which chlorite growth is accelerated and unstable clastics replaced. Thus, it can be used as an approximate boundary for the chlorite isograd.

We collected illite crystallinity data from the carefully disaggregated < 2 micron fraction of fine-grained rocks of the Rhode Island and Wamsutta Formations (i.e., slates and phyllites, coals, thin shale partings, and argillaceous rip-up clasts). This minimized the problem of admixed coarse detrital muscovite, which would cause illite basal peaks to appear anomalously sharp and well-crystallized. From this data we produced a map (Rehmer, Hepburn and Schulman, 1978; Rehmer, Hepburn and Ostrowski, 1979) in which illite isocrystallinity contours act like metamorphic isograds to subdivide zones of increasing thermal alteration (Figure 1). Our data shows an increase in grade toward the south and center of the basin. In the northwest corner of the Narragansett Basin and adjoining Norfolk Basin, conditions are near the upper limits of diagenesis; coals are anthracitic and only 2M mica polymorphs are detected in unoriented X-ray diffraction patterns. Most of the sub-biotite rocks of the Narragansett Basin complex belong within the zone of anchimetamorphism, in which the principal phyllosilicate phases are illite and chlorite. Only in the southern part of the Narragansett Basin do the isocrystallinity contours of the anchizone reflect the same regional pattern found within the higher grade rocks of the greenschist and amphibolite facies. In the north, the low-grade and higher grade patterns appear to intersect at a high angle, particularly near the western margin of the basin near Providence, R.I.

The greenschist facies as defined by illite crystallinity is more areally extensive than that previously mapped on the basis of the first appearance of biotite (Quinn, 1971; Skehan and others, 1979). However, in the southern part of the Narragansett Basin, where the isograds rise rapidly in intensity from sub-biotite to kyanite zone over 3-10 km, the greenschist facies boundary as determined by illite crystallinity closely coincides with the biotite isograd.

The generalized relationship of illite crystallinity to coal rank and metamorphic facies is illustrated in Figure 3. While diagnostic metamorphic minerals are rare megascopically in pelitic rocks of the diagenetic and anchizones, paragonite and pyrophyllite are readily detected by X-ray diffraction and chloritoid may be seen in thin section. Paragonite, considered a diagnostic mineral for the upper anchizone and greenschist facies (e.g., Frey, 1970) was detected in X-ray diffraction patterns of samples from the vicinity of Pawtucket and Providence, R.I. In our work and that of Quinn and Glass (1958) paragonite has only been found in the Narragansett Basin in the upper anchizone and lowermost greenschist facies. Chloritoid also appears in this part of the basin. Although formerly considered to be a mineral of the anchizone (Kubler, 1968), chloritoid typically makes its appearance only in the greenschist facies proper (Frey, 1970, 1978; Kisch, 1974). In the Narragansett Basin, the greenschist facies boundary as mapped by illite crystallinity closely coincides with the chloritoid isograd of Skehan and others (1979). Chloritoid can thus be regarded as a diagnostic mineral for the onset of the greenschist facies in the Narragansett Basin. Pyrophyllite also occurs in the upper anchizone in the Narragansett Basin (e.g., Stop 9). Frey (1978) considers pyrophyllite to be a characteristic mineral of the anchizone in the Central Alps, formed at the expense of kaolinite. Ostrowski (1980, 1981) has studied the chlorites of the Narragansett Basin pelitic rocks in conjunction with our study. Her work demonstrates that the trend toward magnesium enrichment of chlorite with increasing metamorphic grade is part of a continuum that can be extended downward into the diagenetic and anchimetamorphic zones.

The relationship of illite crystallinity to standard coal ranks has been examined in many previous studies, particularly in the Carboniferous tectonic basins of Europe (Frey and Niggli, 1971; Kisch, 1974a,b, 1978; Wolf, 1975; Gill and others, 1977). This correlation is generalized in Figure 3. Increasingly however, as more such studies are done, it is becoming clear that although the generalized correlation holds, there is not a precise one-to-one relationship between illite crystallinity, coal rank and other metamorphic mineral growth. In other words, for different coal basins, there will be some differences in where the

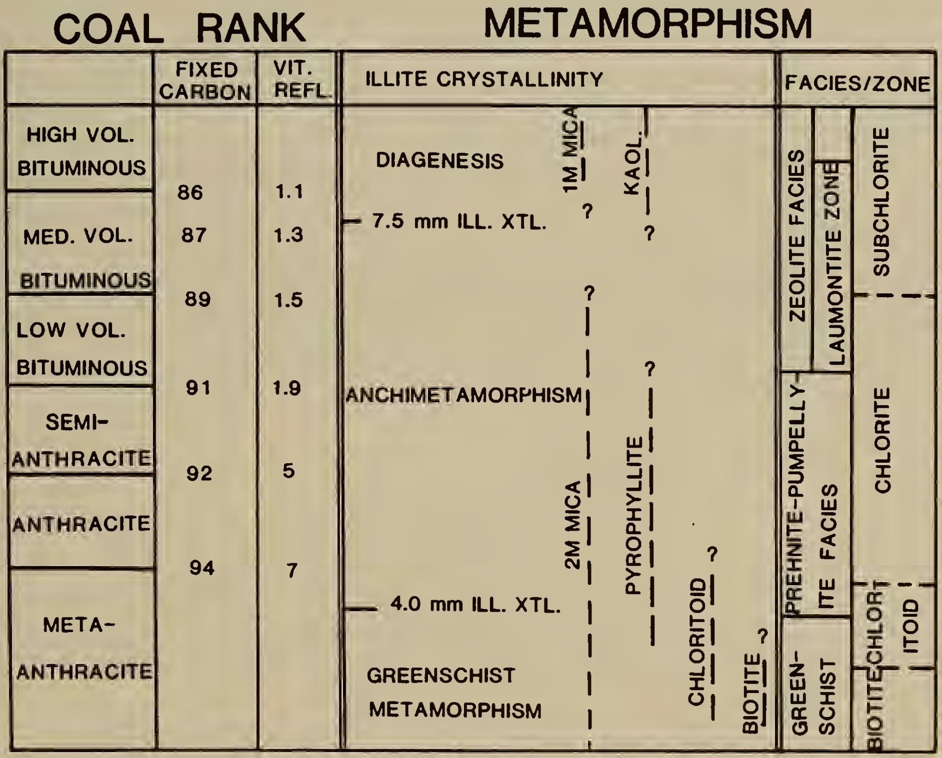

Figure 3. Schematic diagram showing typical relationships of coal rank, illite crystallinity, other mineral paragenesis and standard metamorphic facies and zones. Assembled from several sources. The values for illite crystallinity at zone boundaries given here are those of Kubler (1964). Kubler's 4.0 mm equals our 4.6 mm (Fig. 1) and Kubler's 7.5 mm equals our 7.25 mm. See text for details.

lines are drawn on Figure 3. This is only to be expected; factors leading to clay mineral transformations are somewhat different than for coal. Organic matter is transformed predominantly as a function of temperature and to a lesser extent time. With clay mineral alterations such additional factors as total pressure, various partial pressures (P_{H2O}, P_{CO2}, P_{CH4}, etc.) and composition of pore waters must be considered along with temperature and time.

Correlation of our illite crystallinity data to coal rank has been somewhat hampered by a lack of chemical data for Narragansett coals that conforms to ASTM rules for standard determination of rank using the ASTM classification scheme (see Lyons and Chase, 1979, for a complete discussion of this problem). As expected, the trends in increasing illite crystallinity and increasing coal rank lie in parallel directions. Our data, however, clearly differs from the "standard correlation" shown in Figure 3. In the Narragansett Basin, pelitic rocks with quite high values of illite crystallinity (i.e., poorly crystallized illite) can be found in association with anthracitic coals. For instance, in the northern part of the basin (Mansfield and Plainville, Mass. area) shales whose illite crystallinity values suggest that only diagenetic thermal conditions were attained are found with coals whose mean maximum vitrinite reflectance values (aver. 6.4 and 5.6, respectively, from Raben and Gray, 1979) are more typical of the anchizone.

Wolf (1975) in her work on the Rheinische Schiefergebirge has found two differing paths of illite crystallinity/coal rank correlations that are primarily a function of the geologic and thermal histories of different parts of that basin. One trend, characterized by a high degree of illite crystallinity at relatively low coalification rank (and similar to the correlation of Figure 3) is found in sediments influenced only by the regional effects of subsidence and deep burial. A second trend, in which coalification rank is higher than the degree of illite crystallinity, was found in parts of the Rheinische Schiefergebirge where the sediments were heated by magma. This second trend is quite like that found for the Narragansett Basin coals and sediments. Magmatic intrusions, of which the Narragansett Pier Granite is a surface expression, followed sedimentation in the Permian, and are likely to have caused not only the anomalous illite crystallinity vs. coal rank trend, but also the coking and thermal alteration found in the coals in all but the northernmost part of the basin (Raben and Gray, 1979).

Timing of Structure and Metamorphism

Three patterns of illite isocrystallinity contours (Figure 1) are found within sub-biotite regions of the Narragansett Basin: (1) in the north and west isocrystallinity contours trend northeast-southwest in marked contrast to the Barrovian isograds of the southern part of the basin; (2) sub-biotite contours in the southern part of the basin parallel the Barrovian isograds; and (3) near the basin's eastern margin the linear anchizone-greenschist contour appears likely to be fault-controlled.

The isograd discordance between low-grade terrains of the north and the high-grade terrain of the south may reflect the overprint of two distinct thermal events. In such a model, a low-grade burial metamorphism increases to the southeast but has a higher-grade thermal event, centered near the southwestern corner of the basin, superimposed over it. The intrusion of the Narragansett Pier Granite (276 m.y.; Kocis and others, 1978) has been suggested as at least a partial cause of the highest isograds (Quinn and Moore, 1968; Grew and Day, 1972).

Although their models differ considerably in detail, both Grew and Day (1972) and Murray and others (1979) have found evidence in the southern part of the basin to suggest a two-stage high-grade metamorphism, with the Narragansett Pier Granite intruded at or just after the peak of metamorphism, followed by a late low-grade metamorphism. Thus, a second possibility is that the low-grade burial metamorphism best displayed in the northern part of the basin has been superimposed on the higher grade rocks centered around the Narragansett Pier Granite and has caused retrograde reactions. In support of this model, the rocks of the Narragansett Basin, even the low-grade phyllites, yield uniform apparent K-Ar ages (from biotite and muscovite) of 230-260 m.y. (Zartman and others, 1970; Dallmeyer, 1981). This would suggest that argon retention at the close of Permian metamorphism occurred at approximately the same time in both the northern and southern parts of the basin.

Structure

Slaty cleavage and schistosity is generally well-developed in the argillaceous rocks of the sub-biotite zone Narragansett Basin; many of the coarser clastic rocks of the anchizone have also developed a spaced fracture cleavage. Although we will observe a general increase in cleavage and deformation with rising isocrystallinity isograds, attempts to directly correlate these two features has always proven futile (Kubler, 1967). Dynamic factors, which are important in the formation of schistosity, have no perceptible effect on illite crystallinity. We have found, for example, that the illite crystallinities from slickenside surfaces are essentially identical with those from juxtaposed samples that do not have movement surfaces. On the other hand, increasing temperature, the most important factor in illite crystallinity, and the recrystallization of the phyllosilicates can help to promote the development of a schistosity.

Acknowledgements

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THE DIAGENETIC TO METAMORPHIC TRANSITION IN THE NARRAGANSETT AND NORFOLK BASINS, MASSACHUSETTS AND RHODE ISLAND

Road Log

The trip will start in the unmetamorphosed Pennsylvanian rocks of the Norfolk Basin in Norwood, Massachusetts and proceed southward across the Narragansett Basin, ending at the Jamestown Bridge in the staurolite zone. The last stop is a 15 minute drive from the NEIGC headquarters at the University of Rhode Island, Kingston.

Meeting Place: The trip will assemble in the parking lot adjacent to Rt. 1 of the Holiday Inn, Dedham, Mass. at 9 A.M. The Dedham Holiday Inn is on Route 1 just North of exit #60 from I-95 (Rt. 128). Turn left into the parking lot of the Holiday Inn at the 1st traffic light after leaving the exit ramp North of I-95. Participants traveling from Kingston should allow an hour to an hour and a quarter to reach this meeting place.

MILEAGE

Cum.	S/S	
0.0	0.0	Road log begins at exit from parking lot of the Dedham Holiday Inn onto Route 1; TURN RIGHT (south).
0.2	0.2	Enter Rt. I-95 (Rt. 128) SOUTH. Continue on I-95 to Exit #62.
2.4	2.2	Exit #62 (University Avenue). Bear Right.
2.5	0.1	Turn LEFT at end of ramp.
2.6	0.1	Turn RIGHT onto University Avenue.
3.6	1.0	Turn LEFT at stop sign (by W.W. Grainger, Inc.).
4.3	0.7	Turn RIGHT beyond interstate overpass into Shawmut Industrial Park.
4.8	0.5	Turn RIGHT into parking lot of Walworth Marine Co.; outcrop is behind the buildings by the railroad tracks.

STOP 1. (45 minutes) Norwood Quad. Wamsutta Formation; Shawmut Industrial Park. Diagenetic Zone (K.I. = 9.0-11.6 mm)

This outcrop consists of four fining upward alluvial cycles in the Wamsutta Fm., here mostly sandstone and conglomerate with lesser amounts of reddish and green siltstone and slate. An abundance of sedimentary features can be seen here including cross-bedding, scour-and-fill, pelitic rip-up clasts, and root mottling. The prevailing dip direction of the cross-beds is southwest (Chute, 1966).

Bedding is somewhat variable, averaging N65°E, and is overturned dipping 80°NW. A well-developed fracture cleavage occurs within argillaceous rocks, is weaker in siltstones and absent from the coarser clastics.

In pelitic units this cleavage is particularly well developed adjacent to shear zones. Cleavage generally intercepts bedding at a low angle and dips less steeply than the bedding (approx. N75°E, 60-65°NW). Several shear zones are evident, with slickensided surfaces developed in the pelites. Tension gashes, filled with carbonate, quartz and chlorite, are developed adjacent to shear zones.

The Wamsutta Formation has been mapped both here in the Norfolk Basin and in the northern part of the Narragansett Basin, and it is likely that these two basins were fully merged at the time of sedimentation (Quinn and Oliver, 1962).

Cum.	S/S	
7.3	2.5	Retrace Route to I-95. Enter I-95 (Rt. 128) SOUTH. Stay in right lane and be prepared to exit onto I-95 South.
7.8	0.5	Enter Route I-95 South.
9.7	1.9	Outcrop on left is similar to Stop #1.
21.6	11.9	Leave I-95 at Exit #7A (Rt. 140 South). BE PREPARED TO STOP SUDDENLY.
21.7	0.1	Park with caution on right shoulder adjacent to the exit ramp.

STOP 2. (30 minutes) Mansfield Quad. Rhode Island Formation; cloverleaf of Interstate 95 & Rt. 140, Foxboro, Mass. Lower Anchizone (K.I. = 6.7 mm).

A large section of Rhode Island Formation with complex folding, faulting and possible facies changes is exposed here. A detailed map of this area has been presented in Lyons and Chase (1976).

The lithologies are mostly fluvial graywacke sandstone and dark gray slate and siltstone, with lesser polymict conglomerate. The sandstone is laminated to cross-bedded, and in places contains large pelitic rip-up clasts. Approximately 30 plant species have been described from this locality, and high-ash coal beds were originally exposed along I-95 during its construction (Lyons and Chase, 1976). Mean max. vitrinite reflectance from 11 samples of these coals ranges from 4.8-7.5 (ave. 6.4), dominantly anthracite with minor meta-anthracite (Raben and Gray, 1979).

Bedding is less distinct than STOP #1; and although higher grade, the cleavage is less regular. Cleavage varies greatly with lithology. Fine sandstones and siltstones have a well-developed close-spaced "slaty" cleavage, although massive sands and conglomerates are little affected. Pelitic beds have a wavy, pervasive foliation and have developed a phyllitic sheen, particularly in the dark graphitic rocks. The foliation surfaces in fine-grained rocks show extensive slickensides. Lyons and Chase (1976) have mapped over a dozen faults in this outcrop.

		Continue on Rt. 140 until you can turn around.
22.3	0.6	Re-enter I-95 SOUTH.
30.9	8.6	Exit onto Rt. 123 West (Exit #3B).
31.4	0.5	Base of exit ramp, proceed west on Rt. 123.
33.1	1.7	Turn RIGHT onto May St.
33.3	0.2	Junction May St. and Rt. 1. Park with care. Outcrop is on the east side of Rt. 1.

<u>STOP 3.</u> (30 minutes) Attleboro Quad. Wamsutta Formation; Rt. 1 and May St., South Attleboro, Mass. Diagenetic Zone (K.I. = 9.4-10.8 mm).

Fluvial sequences of red shale, siltstone and sandstone, lithologically similar to Stop #1 can be seen in this outcrop of the Wamsutta Formation, now in the Narragansett Basin. The rocks locally are in a simple dipping sequence (N50°E, 40°NW) with cleavage subparallel to bedding. Only a weak, irregular, wide-spaced fracture cleavage is present in the shale and none is evident in the siltstones and sandstones.

Fine-grained beds are brick red with some green mottling that is irregular and laterally discontinuous. Lidback and Gheith (1980) attribute the red coloration of the Wamsutta to the secondary formation of hematite, and the mottling to the fluctuating Eh-Ph of groundwater during diagenesis.

The transition zone between Wamsutta (red) and Rhode Island (gray) beds is best seen in the vicinity of Attleboro, Mass., where red and gray beds are commonly interlayered. Gray "Rhode Island" shales outcropping on the grounds of the Fuller Memorial Hospital (on the opposite side of Rt. 1 from this stop) have similar diagenetic illite crystallinities (K.I. = 10.2-12.4 mm) despite the pigmentation difference.

Turn around, head SOUTH on Rt. 1.

33.3	---	Junct. May St. and Rt. 1; proceed SOUTH on Rt. 1.
33.5	0.2	Turn LEFT onto Rt. 1A SOUTH. Continue on Rt. 1A to I-95.
34.8	1.3	Turn RIGHT onto I-95 SOUTH.
36.8	2.0	Large outcrops of Rhode Island Formation on left.
40.1	3.3	Leave I-95 at Exit #24 (Branch Ave.).
40.3	0.2	At end of ramp, turn LEFT onto Branch Ave.

40.6 0.3 Turn RIGHT onto North Main St.

41.0 0.4 Turn LEFT into University Heights Shopping Center.

41.2 0.2 Proceed around the Rhode Island Hospital Trust Bank building to outcrops at the rear of the shopping mall.

STOP 4. (30 minutes) Providence Quad. Rhode Island Formation; University Heights Shopping Center, Providence, Rhode Island. Lower-Upper Anchizone boundary (K.I. - 6.0 mm).

Interbedded graphitic phyllite, siltstone, sandstone, and minor small-pebble conglomerate outcrop along the ledge at the rear of the shopping center. The primary cleavage is generally along bedding, but both are irregular in orientation. Cleavage is developed in all lithologies except the conglomerates. Phyllites have a prominent fissility; secondary slip-cleavage producing a prominent, near horizontal crinkle lineation is found in the graphitic phyllites.

A faulted asymmetrical anticlinal fold is evident near the south end of the outcrop. Slickenside surfaces on graphitic phyllites, and the wrapping of the cleavage in phyllites around more resistant sandstone layers indicate an abundance of differential movement surfaces.

Coarse detrital mica is very evident in the sandstones here. Because of the prevalence of coarse detrital muscovites in sediments of non-marine, intermontane basins, extra care must be taken to avoid the admixture of this well-crystallized material into the 10 A fraction when undertaking illite crystallinity studies. We sampled no lithologies coarser than siltstone for the study and always used the most fine-grained rock available. Disaggregation of the samples, by oxidation of organics and ultrasoneration, avoided grinding of coarse detrital grains into the fine fractions. Finally, analysis of illite crystallinity was only performed on the less than 2 micron fractions of the disaggregated samples.

41.1 0.2 Return to North Main St. Turn RIGHT (North).

41.6 0.2 Turn LEFT onto Branch Ave. again.

42.0 0.4 Turn LEFT onto I-95 SOUTH.

42.1 0.1 Bottom of ramp, re-enter I-95 SOUTH.

44.1 2.0 Junct. I-95 and I-195. STAY on I-95 SOUTH.

47.0 2.9 Leave I-95 at Exit #16, Rt. 10, Cranston, (Also marked, "To Reservoir Ave.").

47.4 0.4 Enter Rt. 10 NORTH.

48.8 1.4 Exit at Cranston St. (also marked "Industrial Park"). Stay in left lane of exit ramp.

49.0 0.2 Turn LEFT at bottom of ramp.

49.1 0.1 Turn LEFT onto Cranston St.

49.8 0.7 Branch of the Cranston Public Library on left.

50.0 0.2 Turn RIGHT onto Chestnut Hill Ave.

50.1 0.1 Outcrop on right in yard.

STOP 5. (30 minutes) Providence Quad. Rhode Island Formation, Cranston, Rhode Island. Upper Anchizone - Greenschist Facies boundary.

Private Property. Please be careful of lawns and gardens.

The ledge behind the house consists of homogeneous, organic-rich, dark gray siltstone and fine-sandstone with thin pelitic partings. Although bedding is indistinct, it is parallel to cleavage, as indicated by the orientation of large, abundantly preserved plant fossils found in this outcrop. Cleavage occurs throughout, but is a somewhat irregular fracture cleavage in the arenaceous beds. A secondary crinkle lineation occurs within the phyllites. Traces of chloritoid, an index mineral to the anchizone-greenschist boundary (Frey 1978), are found microscopically in the phyllites here. Ilmenite megacrysts, commonly sheathed in thin layers of "pressure shadow" quartz and chlorite, are prominent in the phyllites.

Some of the white mica detectable in x-ray diffraction patterns from this and other localities in the Providence area (Quinn and Glass, 1958) is paragonite, which is not optically distinct from muscovite. Paragonite, with a basal (001) peak of 9.7 Å, creates a double-peak or high-angle shoulder on the 10 Å muscovite peak. Thus illite crystallinity measures are anomalously broad (K.I. = 5.5 at this locality) compared to what data would be from paragonite-free samples, and supplementary petrographic information must be used to aid in the construction of isocrystallinity contours.

50.2 0.1 Return to Cranston St. Turn RIGHT and proceed south.

50.4 0.2 At light, turn RIGHT; STAY on Cranston St.

50.6 0.2 Turn LEFT onto Dyer St.

51.1 0.5 Continue straight at light (Budlong Rd.).

52.6 1.5 Turn LEFT (Marked "To Rt. 2, Reservoir Ave.").

52.7 0.1 IMMEDIATELY turn RIGHT into Chateau Sur Crest Apartments and park.

STOP 6. (15 minutes) Providence Quad. Lowermost greenschist facies (incipient biotite growth).

A very small outcrop, no hammers please. (You may collect very similar material during our lunch stop). Very well cleaved, gray phyllite with prominent ilmenite porphyroblasts. This outcrop is essentially on the upper anchizone-greenschist boundary. Small incipient biotites are seen in thin section, forming from chlorite. The ilmenite porphyroblasts are commonly rimmed by chlorite, thus giving them a duller luster in hand sample than is typical for ilmenite.

This is about the upper limit at which illite crystallinity data can be effectively used to interpret low-grade conditions, because (1) the mica is no longer interlayered with other phyllosilicates, and thus muscovite peak widths no longer change with increasing grade; and (2) Biotite with an (001) spacing of 10.1 Å produces a low-angle broadening on the 10 Å muscovite peak.

52.7	---	From Chateau Sur Crest Apartments, turn RIGHT onto Reservoir Avenue.
52.9	0.2	At light, cross Route 2.
53.0	0.1	Turn LEFT into Garden City Shopping Center. Proceed to Newport Creamery. LUNCH and REST STOP. For those who wish to collect phyllite with ilmenite porphyroblasts similar to Stop 5, proceed to the small scattered outcrops on the hill behind the Old Colony Bank.
53.0	---	Exit from Garden City Shopping Center. Turn LEFT onto Route 2 South (Reservoir Avenue).
53.5	0.5	Turn RIGHT. Entrance to Rt. 37 EAST (marked "To Air Terminal and 95").
53.8	0.3	Top of ramp; proceed east on Rt. 37.
54.3	0.5	Exit onto Pontiac Avenue.
54.5	0.2	At bottom of exit ramp, turn RIGHT onto Pontiac Avenue, toward Howard Industrial Park.
55.2	0.7	Turn LEFT (Stay on Pontiac Avenue).
55.3	0.1	Turn LEFT into the industrial park.
55.6	0.3	Proceed to RR tracks at bottom of hill and park.

STOP 7. (45 minutes) East Greenwich Quad. Rhode Island Formation. Lower Greenschist Facies.

Large glacially polished outcrops on both sides of the road. Metasandstone, siltstone, and conglomerate predominate here with minor amounts of phyllite to schist. Muscovite regrowth can now be seen megascopically. Ilmenite porphyroblasts are common in the more pelitic layers. Bedding strikes generally northward and dips 25° to the east. The principal cleavage approximately parallels bedding, but is not prominent in the massive sandstone and conglomerate beds. A secondary cleavage is seen cutting all the rock types and causing a crinkle lineation in the more pelitic layers. Excellent sedimentary features are prominent even at this grade of metamorphism and include cross-bedding, scour-and-fill, argillite rip-up clasts, and sandstone dikes. Tectonic injection of pelite into sandstone and conglomerate beds is also seen, particularly on the polished outcrop east of the road.

55.6 --- Continue straight.

55.8 0.2 Turn LEFT at T-intersection.

56.0 0.2 Turn RIGHT onto Pontiac Avenue.

56.5 0.5 Bear RIGHT onto Rt. 37 EAST (toward Warwick and I-95).

57.0 0.5 Exit from Rt. 37. Take I-95 North toward Providence; proceed north on I-95.

62.7 5.7 Bear RIGHT; take I-195 East.

66.9 4.2 Mass.-Rhode Island border, entering Massachusetts. Continue east on I-195.

71.2 4.3 Leave I-195 at exit #2, Rt. 136 South toward Newport, Rhode Island.

71.5 0.3 At bottom of ramp, turn RIGHT onto Rt. 136 South.

72.6 1.1 At state line, park by outcrop on right.

STOP 8. (15 minutes) East Providence Quad. Rhode Island Fm. Upper Anchizone (K.I. = 5.3 mm).

The rock is a well-cleaved, homogeneous light gray-green siliceous and feldspathic siltstone to siliceous slate with small irregular chlorite knots. Bedding is at a high angle to the cleavage and is seen by color differences and chlorite concentrations along bedding surfaces. The bedding strikes N30°E and dips 20°SE. The cleavage is variable, striking N50°W to N65°W and dipping 30° to 40°NE. The homogeneous siliceous/feldspathic nature of the siltstone here is unusual in this area of the Narragansett Basin and may represent a volcanogenic sediment.

72.6	---	Continue South on Rt. 136 into Rhode Island. Stay on Rt. 136 to Mt. Hope Bridge.
80.4	7.8	Toll booth, Mt. Hope Bridge (30¢ toll). Cross bridge.
81.4	1.0	At south end of bridge, bear LEFT on Boyd St. (marked "138 and to 24 North").
81.8	0.4	Turn LEFT onto Common Fence Point Rd.
82.8	1.0	Turn RIGHT onto Rt. 24 SOUTH.
84.8	2.0	Park by large outcrop on both sides of Rt. 24; Butts Hill.

STOP 9. (15 minutes) Prudence Island Quad. Rhode Island Fm.; Butts Hill.
Upper Anchizone (K.I. = 5.7 mm).
WATCH FOR POISON IVY.

The rocks are homogeneous, well cleaved to fissile, very dark-gray, organic-rich slates and siltstones with minor amounts of sandstone. Small knots of recrystallized chlorite give a fleckshiefer appearance. Bedding and cleavage both dip to the south at a shallow angle, although cleavage forms at a low angle to the bedding. The cut appears to be a simple dipping sequence without apparent major structural complexity. All the units are very well cleaved, with the exception of thin sandstone beds that have only a more widely spaced cleavage.

Note that we have come back down grade metamorphically from the last several stops. The rocks here are typical of those in the center of the low-grade metamorphic trough in the southern Narragansett Basin, both metamorphically and sedimentologically. The rocks are much more homogeneous on the scale of an outcrop here, than in the northern part of the basin (e.g., Stop 3). Fine-grained lithologies are widespread in this part of the basin, and some of the thickest coal seams are found in the Portsmouth, R.I. area (J. Skehan, pers. comm.).

84.8	---	Continue south on Rt. 24, which merges with and becomes Rt. 114.
86.2	1.4	Turn RIGHT into small lane parallel to the main road.
86.4	0.2	Proceed along lane until opposite the large roadcut on the east side of Rt. 114. Park; walk across highway to the outcrop. Watch carefully for traffic!

STOP 10. (15 minutes) Prudence Island Quad. Rhode Island Fm. Turkey Hill.
Upper Anchizone (K.I. = 5.5 mm).
WATCH FOR POISON IVY.

The rocks are well-cleaved, homogeneous gray-green, chloritic siltstone to argillaceous siltstone with scattered large pyrite porphyroblasts and small secondary knots of chlorite. Minor ankerite is present and phyrophyllite occurs as a fine-grained silky sheen on some foliation surfaces (confirmed by x-ray). The bedding here is obscure, only easily observed where thin pelitic beds occur within the siltstones. It dips at a shallow angle to the southwest and is itself transected by the prominent cleavage at a low angle.

The notable differences between this outcrop and that seen at Stop 9 is its coarser grain-size and its depositional environment; they are at approximately the same metamorphic grade.

86.4	---	Rejoin Rt. 114 and continue south.
92.1	5.7	Turn RIGHT. Follow signs to the Newport Bridge.
93.8	1.7	Rotary; go around 270° onto Rt. 138 West (marked "To Jamestown and New York").
94.5	0.7	Cross Newport Bridge.
97.1	2.6	Toll booth at west end of bridge (toll $2.00); continue west on Rt. 138.
98.0	0.9	Turn LEFT; continue on Rt. 138 West.
99.3	1.3	Pull off on right and park just before the Jamestown Bridge (at Mr. Pipe's Restaurant). Walk down dirt path at right to the shore.

<u>STOP 11.</u> (45 minutes) Wickford Quad. Rhode Island Formation. Amphibolite Facies; Staurolite Zone.

Along the shore here are beautiful exposures of interbedded mica schist, metasandstone and stretched pebble metaconglomerate that strike generally north with a moderate dip to the east. The mica schist is fine-grained, well foliated and varies from silvery-gray to dark-gray depending on the carbon content. Abundant porphyroblasts of garnet and "turkey track" staurolite to several cms. in length occur in the schist and on pelitic partings in the sandstone and conglomerate. The staurolite has locally been retrograded to chlorite. Grew and Day (1972) present a detailed discussion of the metamorphic textures and mineralogy for the rocks at this locality. Plant fossils occur in graphitic mica schist, interbedded with the garnet-staurolite mica schist, along the shore 1500 feet south of this exposure (Quinn, 1971, p. 50). The fluvial sequences of conglomerate-sandstone-shale seen at low grade outcrops earlier today (e.g., Stops #1, #3) can still be recognized in spite of the changes brought about by increased metamorphism and tectonic thinning.

END OF TRIP

Proceed to the N.E.I.G.C. headquarters at the University of Rhode Island in Kingston by continuing on Rt. 138 West for approximately 12 miles. Rt. 138 joins Rt. 1 South for 3 miles of this route, then proceeds westward to Kingston.

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THE GEOLOGY OF PRECAMBRIAN ROCKS OF NEWPORT AND MIDDLETOWN, RHODE ISLAND

by

Nicholas Rast
Department of Geology
University of Kentucky
Lexington, KY 40506

and

James W. Skehan, S.J.
Weston Observatory
Dept. of Geology & Geophysics
Boston College
Weston, MA 02193

INTRODUCTION

The older rocks of Newport, Rhode Island have been extensively described (full bibliography in Quinn, 1971). In recent years these rocks were discussed by Kay and Chapple (1976), mapped by Moore (1975), and Smith (1978) has dated the Newport granite which intrudes the bedded rocks. The bedded succession has been referred to, on incomplete evidence but correctly, as a metasedimentary sequence overlain by volcaniclastic rocks (Quinn, 1971). Each of the two sequences is of a considerable thickness and the informal terms, Newport and Price's Neck formation have been given to the metasedimentary and the metavolcanic sequence respectively (Rast and Skehan, in press 1981). The Newport formation was thought to be possibly Lower Cambrian (Murray and Skehan, 1979), but the present mapping establishes the rocks as Precambrian.

The structure of the area so far has been incompletely described although it has been recognized that the bedded rocks have undergone polyphase deformation (Kay and Chapple, 1976). We have remapped the critical contacts and have established a general sequence of stratigraphic and structural events with special attention being paid to sedimentary facing and extensive refolding.

GENERAL SETTING

In Newport and Middletown townships (Fig. 1) the Precambrian rocks outcrop in western Newport, in southern Newport on Cliffwalk, and on Sachuest Point and Gould Island of the Sakonnet River (Fig. 1). The western Newport outcrop, being the largest, has been called the Main Outcrop.

In the Main Outcrop the metasedimentary strata are folded into overturned recumbent folds, while the volcanogenic rocks are in upright folds. In both cases these folds (F_1) are refolded by small second folds (F_2). Both sets of folds have axial plane cleavages (S_1 and S_2) but the most pervasive cleavage is the S_2. Contemporaneous and later faults are abundant.

The contact between sedimentary and volcanogenic rocks (Table 1) is in most cases a fault although at Stop 4 (Fig. 1) a small outlier of Price's Neck formation grades down into metasedimentary rocks, and in the northern part of Stop 6 (Fig. 1) volcanogenic layers can be recognized as interbeds in the metasedimentary rocks. At both stops and also at Locality A (Fig. 1) the Newport formation faces into the Price's Neck formation. Therefore, the collective evidence is that volcanogenic rocks of the Price's Neck formation are younger than the metasedimentary rocks of the Newport formation and that,

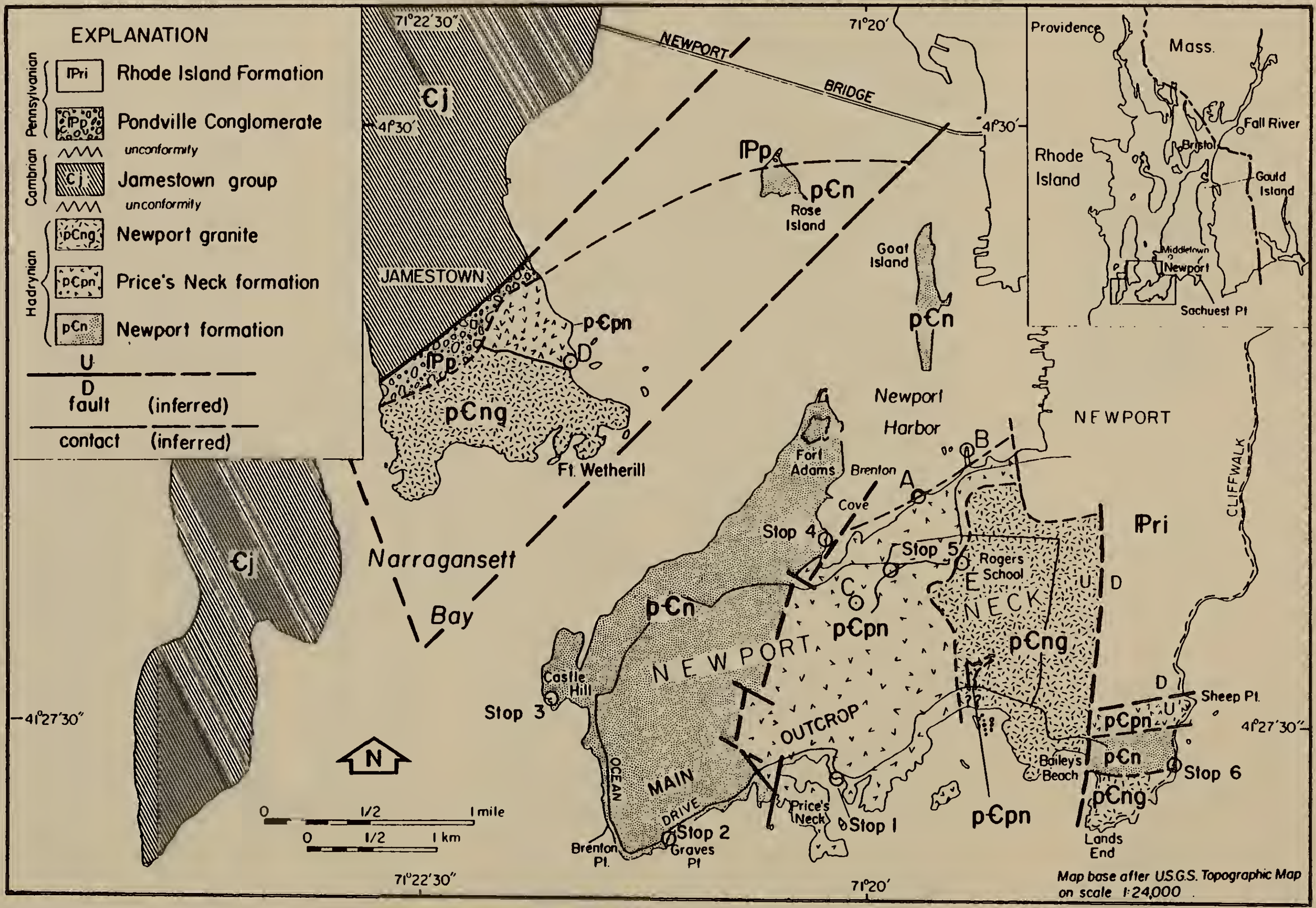

Figure 1. Geological map of a portion of Newport and Jamestown, Rhode Island showing field trip stops and localities referred to in text.

despite the appreciable recumbent early folds, the succession as a whole faces upward. Within the Newport formation the F_1 overturned to recumbent folds cause rapid and sudden inversions of sedimentary facing.

Price's Neck formation (purple volcaniclastic turbidites and tuffs in felsic volcanogenic sequence) - Units 1-4.	
Newport formation	Ft. Adams member - upper part (diamicite or olistostrome of disjointed graywacke turbidites, quartzites, dolomite, and serpentine).
	Ft. Adams member - lower part (semipelites with interbedded quartzite and olistoliths).
	Graves Point member (pelites and siltstones, with thin turbidites and volcanogenic intercalations).
	Brenton Point member (turbidites, felsic to intermediate pelitic tuff).
	Castle Hill member (turbidites, slates and tuffs).

Table 1. Stratigraphic succession of Newport and Price's Neck formations of Newport and Middletown, Rhode Island (modified from Rast and Skehan, in press, 1981).

STRATIGRAPHY

On the basis of sedimentary facing, Rast and Skehan (in press, 1981) have divided the Newport formation as follows from the bottom upward:

Castle Hill member - This member consists mainly of composite graywacke beds of sandstone and slate 30 cm to 1.5 m thick, the sandy part grading up into slate. Thicker graywacke beds commonly show soft-sediment deformation including chaotic bedding, slump folding, and intraformation shale-fragment breccias. These features suggest that these rocks are fluxoturbidites deposited on a slope. A few beds of conglomerate, limestone, and dolomite concretions are present in restricted parts of the section.

Brenton Point member - Upward grading sandstones or turbidites of the type found in the Castle Hill member grade up into thin-bedded siltstones interlayered with thin felsic volcanic units. The felsic units, that are usually buff weathering and porcellanitic, contain few sedimentary structures except for ubiquitous lamination, and are not traceable for distances greater than several hundred feet. At the contacts with the Brenton Point and Castle Hill members, these volcanic horizons are particularly abundant and show slumping.

Graves Point member - This member consists essentially of fine-grained deposits of siltstones, pelites and volcanogenic intercalations. The pelites vary from true phyllites to metasiltstones, are variably gray to green to maroon and contain occasional thin turbidites. The Graves Point member on the western side of the Fort Adams peninsula (Fig. 1) gradually passes to the east into chaotically disturbed rocks of the Fort Adams member.

Fort Adams member - This member is comprised of fragments of "pull-apart" beds and exotic blocks in a fine-grained pelitic and semipelitic matrix. On the eastern side of the Fort Adams Peninsula the member contains elongated fragments of disjointed turbidites, white quartzites, buff weathering calc-silicate rock, and carbonates. In addition, there are rarer fragments of mafic and, at Locality A (Fig. 1), ultramafic rocks. Toward the top, the Fort Adams member passes into volcaniclastic and slaty rocks interbedded with disrupted feldspathic sandstone horizons (Fig. 1, Stop 4). This relationship suggests that the disruption has been produced during the sedimentation rather than tectonically. The tectonic deformation produced particularly chaotic structures as is also seen at Stop 6.

Price's Neck formation - In the Main Outcrop of Newport (Fig. 1), the Price's Neck formation consists of three units, from bottom to top:

Unit 1. Agglomerate breccias (in part at least representing lahars) conglomerates, and associated soft sediment deformed coarse tuff.

Unit 2. Thinly bedded tuff and laminated sediments with possible rhyolite flows.

Unit 3. Graded beds of aquagene tuffs fining upward into siltstones and slates.

At Sachuest Point and Gould Island (Fig. 1) a thick unit of essentially volcanogenic conglomerates appears to fine downward into Unit 3. Thus, these conglomerates appear to represent a higher Unit 4 of the sequence.

Minor Intrusions

In many localities the Price's Neck formation is crosscut by felsic dikes. In the central part of the Main Outcrop a large number of dikes seem to form a stockwork of felsic intrusive bodies that was probably a feeder to the volcanogenic rocks. All formations are cut by later mafic dikes (Moore, 1975). At Locality D on Jamestown (Fig. 1) these dikes crosscut first folds and are folded by the second folds. Therefore, these dikes are post-F_1 and pre-F_2.

Newport Granite - The intrusive contact of the Newport granite is well exposed in at least three localities: 1) on Cliffwalk between Sheep Point and Lands End, 2) on Cliffwalk at Bailey's Beach, and 3) near Rogers High School (Loc. E, Fig. 1).

The Newport granite, which at Cliffwalk intrudes the olistostrome of the Fort Adams member of the Newport formation, is responsible for widespread contact metamorphic hornfelsing or spotting of both the Newport and Price's Neck formations of Cliffwalk, and the Price's Neck of the Main Outcrop. The spotting decreases westward so that most of the metasedimentary rocks of western Newport are not appreciably contact metamorphosed. The granite, therefore, is later than all the bedded rocks of either the Newport formation or the Price's Neck formation.

The Newport granite is a coarse granitic rock varying in composition between true granite and adamellite. In places it is coarsely porphyritic. Internally the pluton is cross-cut by aplites and quartzo-feldspathic pegmatites and relatively smaller bodies of fine-grained granite. The intrusion is appreciably deformed and is particularly affected by faults of several ages (Stop 6). It has a whole rock Rb/Sr date of 595± 12 Ma (Smith, 1978), and in Fort Wetherill, it is cut by mafic dikes of northwest to southeast trend.

STRUCTURE

The Newport and Price's Neck formations are involved in two principal fold-generating deformations. The first folds in the metasedimentary Newport formation are strongly overturned to the east and southeast and in the west of the Main Outcrop are recumbent and sub-isoclinal to isoclinal. The second deformation produces only relatively small folds that verge to the east and northeast, have fold axes whose trend averages NE-SW, and are associated with a generally low-lying cleavage. There is possibly a third episode of folding on an approximately north-south axis that is responsible for changes of dip of the S_2 cleavage.

In the Price's Neck sequence, the first folds are common, can be identified from reversals in the direction of sedimentary facing on the S_2 cleavage, and have a dominantly, persistent trend of approximately E-W, but also rare NE trends. Second folds are less frequent, are generally small and variable but with a dominant trend of approximately E-W. The second cleavage in the Price's Neck formation is somewhat steeper than in the Newport formation. The difference in style of folding is attributed to the ductility contrasts between the metavolcanic and metasedimentary rocks.

A fairly low-lying S_2 cleavage can also be recognized in the granite at Bailey's Beach (Fig. 1). Although the granite is commonly affected by a steep foliation-like repetitive parting structure, it is clearly not a feature of the first period of deformation because at Cliffwalk (Stop 6) granite cross-cuts the already deformed and once cleaved metasediments of the olistostrome and has a chilled contact against them and both are cut by prominent NE-striking S_2 cleavage. The S_1 cleavage of Cliffwalk commonly strikes E-W to NE. The granite has been intruded prior to the movements that generated S_2 cleavage, but later than those that have generated S_1 cleavage. The mafic dikes that cut granite and metasedimentary and metavolcanic rocks, also cross-cut folds of the first deformation, but are affected by F_2 folds and S_2

cleavage.

To summarize the structural-stratigraphic relationships, the following general succession of events is indicated:

1. Deposition of the Newport formation.
2. Deposition of the Price's Neck formation.
3. Deformation of the above sequence by F_1 movements.
4. Intrusion of Newport granite and some felsitic and appinitic dikes.
5. Intrusion of mafic dikes.
6. Deformation of the above formations and intrusives by F_2 movements.
7. Uplift and erosion of these rocks prior to deposition and deformation of fossiliferous Middle Cambrian marine sediments as well as later deposition and deformation of fossiliferous Pennsylvanian fluvial sedimentary rocks.

STRATIGRAPHIC AND STRUCTURAL CORRELATIONS

The metasedimentary and metavolcanic succession of Newport, Rhode Island has been recognized as Precambrian by virtue of being cross-cut by the Newport granite that is just under 600 million years old. In the area there are also fossiliferous Middle Cambrian rocks (Skehan and others, 1978; Skehan, Rast and Logue, this volume), ranging upward possibly to Upper Cambrian, and also strata of Pennsylvanian age (Quinn, 1971). All of these rocks are appreciably deformed, but the ages of deformation at present are not completely clear except that there must have been a Late Precambrian orogeny, a polyphase post-Middle Cambrian to pre-Pennsylvanian folding and mafic dike intrusion episode; and a late Pennsylvanian-Permian orogeny, the Alleghanian orogeny.

At least the first Precambrian episode (pre-Newport granite) can be attributed to the Cadomian II (Avalonian orogeny) that manifests itself especially well in Anglesey, North Wales as the Monian orogeny (Greenly, 1919, Rast and others, 1976; Rast, 1980; Skehan and Rast, 1981), the approximate age of which is 620 Ma (Wood, 1974). This may be the same as the Virgilina disturbance or orogeny in the Slate Belt of the southern Appalachians described by Glover and Sinha (1973). The polyphase folding and dike intrusion episode recorded in the Cambrian rocks of Jamestown, (Skehan and others, 1978; and Murray and Skehan, 1979) may bear no relationship to the Taconian or Acadian orogenies of New England if the preliminary conclusions of Kent and Opdyke (1978) are valid. They conclude, on paleomagnetic evidence, that the Avalonian platform rocks of southeastern New England were in the southern hemisphere during Devonian time and were far distant from the rocks of the North American plate with which they have been associated since approximately Pennsylvanian time.

The rocks of Pennsylvanian age of the Narragansett Basin have undergone polyphase folding, metamorphism, and igneous intrusion during the Alleghanian orogeny (Quinn, 1971; Skehan and others, 1976; Skehan and others, 1979; and Skehan and Murray, 1980). The Alleghanian orogeny may have resulted from a collision produced as the Avalonian plate was being pushed against the North American plate.

ROAD LOG AND GUIDE

The locations of field stops for this excursion are shown on Figure 1; certain features will be illustrated in greater detail in subsequent figures. The directions in this guide are designed for smaller self-led groups, and therefore, differ slightly from the route which we will actually follow due to easier access to certain stops as a result of special permission of landowners.

Mileage

0.0 Start trip at the east end of the Newport Bridge at junction of Routes 138 and 238. Those who come from the north or west may approach this location using Route 138 east; those coming from the north and/or east may do so via Route 138 west. Proceed from the Newport Bridge south on 238 following the signs to Newport and the scenic Ocean Drive. These will bring you to Memorial Boulevard W. via America's Cup Avenue.

1.1 Thames Street. St. Mary's Church, where in 1953 John Fitzgerald Kennedy was married to Jacqueline Lee Bouvier, is on the right.

1.4 Junction with Bellevue Avenue; turn south (right), Tennis Hall of Fame on left; along Bellevue note signs to many of the famous Newport Mansions such as Mrs. Astor's Beechwood and Salve Regina Newport College.

3.6 Follow Bellevue Avenue past Ledge Road at (3.45 miles) to Ocean Drive; turn left on Ocean Drive and continue to Stop 1. Rocks seen en route include the Newport granite (Fig. 1) and the Price's Neck volcaniclastic rocks.

5.25 Pull over onto the shoulder of the road at west end of Goose Neck Cove, north of Ocean Drive.

Stop 1. Price's Neck formation, Unit 3, south of Ocean Drive (Fig. 1).

Geological features of general interest include:

a) Original features of sedimentation including graded tuffs and lapilli agglomerates. The tuffs have thin laminations of pelite and consequently in places show strong soft-sediment deformation including slump folding, pull aparts and the isolation of slump folds as mudballs.

b) The structure is complex and involves the repetition of subisoclinal folds with steep axial planes and fairly steep axes attributable to the F_1 episode of folding. Variable in intensity, the S_2 cleavage cuts across the early folds and in places kink-like F_2 folds are observed. The graded beds, with their fine pelitic tops, are metamorphically spotted and have developed an apparent reversal of grading. The spots, which appear to be retrogressed cordierite crystals, are unoriented with respect to the first episode of deformation but in places have a weak orientation with respect to the second.

Specific features may be observed at the following points (Fig.2):

1-1. A. An anastomosing syn-deformational slide.
     B. A fragment of a soft sediment fold may be observed.

1-2. An F_1 fold, determined on the basis of graded beds, plunges west at 75°. This fold is cut by faults showing a few inches of displacement.

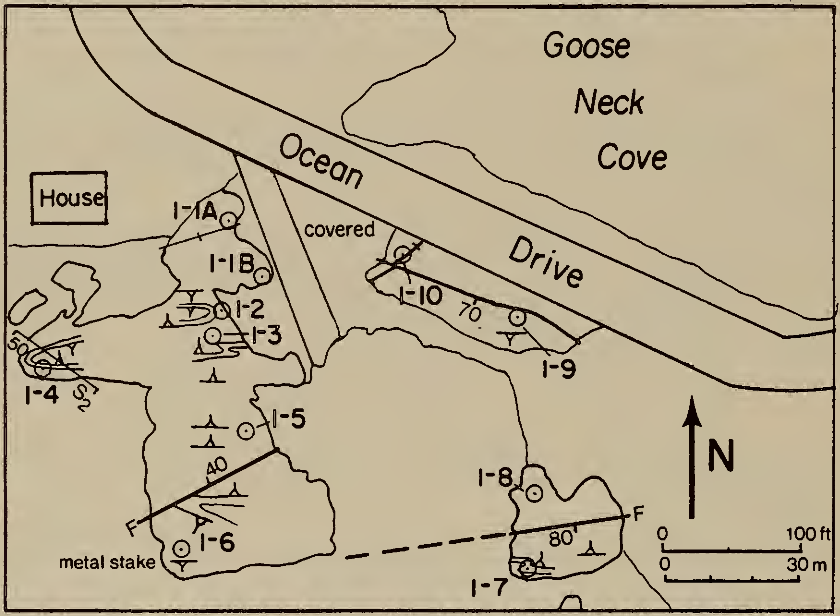

Figure 2. Sketch map of Stop 1, south of Goose Neck Cove and Ocean Drive, showing location of selected geologic features of the Price's Neck formation.

1-3. An F_2 fold is recognized on the basis that S_2 cleavage is axial planar to the folds and the topping direction going north does not reverse itself.

1-4. An F_1 fold is determined on the basis that the later cleavage (S_2) cuts across both limbs of the fold which top as shown on Figure 2. Just north of this fold there is excellent reversal of grading due to thermal spotting.

1-5. Vein of jaspilitic quartz. Nearby is a bed of agglomeratic lapilli. Beds top to the north.

1-6. Using the iron stake as a marker one may examine the beds nearby to determine reversal of topping direction in an F_1 fold (Fig. 2). A fault of small displacement cuts across the nose of an F_1 fold having a coarse lapilli agglomerate bed as a marker horizon.

1-7. On the outcrop just east of 1-6 may be seen an F_2 fold topping to the north.

1-8. Well developed soft sediment deformation.

1-9. Graded beds top to the south; S_1 cleavage (N. 80°W.; 75°S); S_2 cleavage (N. 40°W.; 45°SW).

1-10. Mylonitized selvage on fault (N. 50°E; vertical) offset 0.3 m by late fault (N. 65°W.; 60 SW).

Proceed west on Ocean Drive to South entrance to Brenton Point State Park.

Mileage

6.1 Junction of Ocean Drive with Harrison Avenue on right (north). Turn right into the southern entrance to Brenton Point State Park and park. Cross Ocean Drive with caution and walk left (east) along the seawall to a point 25 m from the Park entrance where you will have an excellent view of the F_1 fold structure.

Features to be noted here include:

A. Stratigraphic succession as noted on Figure 3.

B. A series of upright F_1 anticlinal and synclinal folds overturned to the west with polyphase structures superimposed on them, well displayed on the shore even at high tide. These F_1 folds are cut by the dominant low-lying S_2 cleavage, produced, along with the F_2 folds

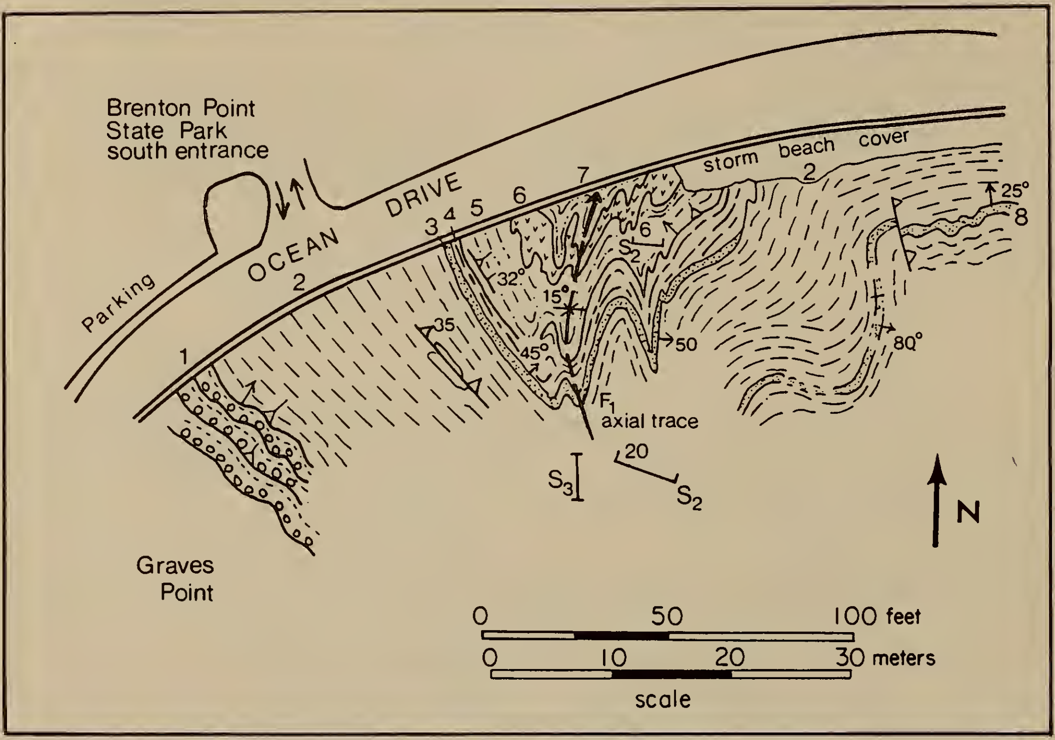

Figure 3. Sketch map of prominent F_1 fold in Graves Point member of the Newport formation cut by S_2 and S_3 cleavages. Lithologic units are from oldest to youngest:

1. Interbedded maroon and pale green sandstone having well developed graded beds (turbidites) toward the base.
2. Dominantly finely layered maroon siltstones and sandstones with some green siltstones and buff weathering tuffs.
3. Buff weathering lapilli tuff.
4. Finely layered maroon siltstone.
5. Interbedded dominant green siltstone with thin salmon pink slate beds.
6. Buff weathering porcellanitic tuff beds.
7. Maroon siltstone and sandstone.
8. Buff weathering tuff bed in Unit 2.

to which it is axial planar, as a result of flattening. S_2 is a transposition cleavage, a feature well displayed in the eastern part of the map area (Fig. 3) where the beds are at a high angle to S_2. S_3 is an upright spaced fracture cleavage (N. 10°W; vertical), rarely observed either in the Precambrian rocks of Newport and Middletown or in the Cambrian rocks of Conanicut Island. Nevertheless, this is the approximate orientation of the axial plane of Alleghanian folds affecting Pennsylvanian rocks of the Narragansett Basin exposed a short distance to the north of Newport.

Return to Brenton Park and vehicles and continue west and north on Ocean Drive.

Mileage	
6.6	Brenton Point on left (south)
6.8	Jetty on left; on a clear day there is a good view of Beavertail Lighthouse to the southwest on southernmost Conanicut Island whose rock-bound shore consists of fossiliferous Cambrian phyllite, the subject of another field trip by Skehan, Rast and Logue (this volume).
7.0	Turn right at north entrance to Brenton Point State Park and park. Because of restrictions on parking near Castle Hill (Stop 3), especially during the tourist season. it may be necessary to park here and walk north along Ocean Drive.
7.25	Outcrops on right consist of inverted turbidite beds up to 1.3 m thick of the Castle Hill member on the front lawn of Mr. and Mrs. Raymond U. Esposito.
7.4	Winans Avenue on right.
7.55	Turn left onto paved access road to the Inn at Castle Hill.
7.7	Turn left again onto unpaved access road near the cottages of the Inn at Castle Hill. Walk to the nearby outcrops that form the shoreline cliffs.

Stop 3. Castle Hill. Castle Hill and Graves Point member of the Newport formation.

A traverse will be made from the shoreline exposures in front of the most westerly of the Cottages of the Inn at Castle Hill to the Lighthouse just south of the Inn at Castle Hill itself. Certain features which may be seen at only one location or other structures or special features which are unusually well displayed at a particular location are noted along the line of traverse (Fig. 4).

This area preserves a great variety of geological features unusually well displayed. A suggested route, with a number of easily recognized checkpoints may be followed to obtain a synoptic understanding of the major features of the geology

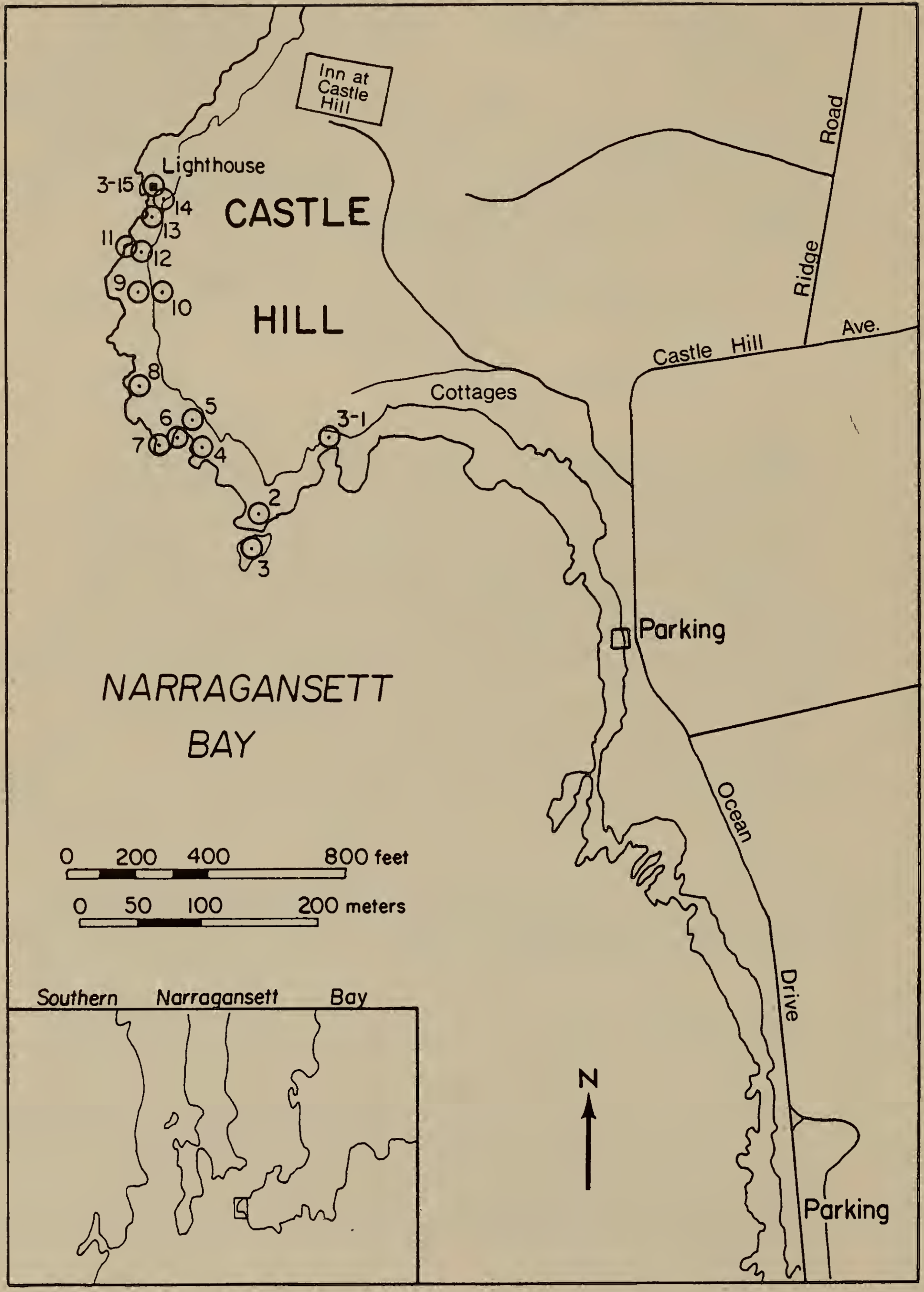

Figure 4. Index map to stations of Stop 3 on the geological traverse along Castle Hill.

of this part of the island.

3-1 to 3-3. Throughout this traverse there is a well developed sequence, one part of which is developed between 3-1 and 3-7, and a second which together with the first is well displayed in the second half of the traverse. The first part of the sequence consists of upward fining graded beds commonly called turbidites, maroon and green, generally thick (from 5-10 cm to 1-1.5 m) with interbedded, finely laminated gray, and alternating gray and maroon siltstones, and maroon and green slates, and gray, white weathering porcellanitic volcanic tuffs and lapilli tuffs.

Throughout the second half of the traverse there is a strong color and grain size contrast as the succession consists dominantly of: pale to dark green chloritic siltstones, maroon siltstones and slates, gray to white weathering porcellanitic tuffs, and minor finely layered gray to greenish siltstones and phyllite of the Graves Point member. This and the previously described section contain sills and dikes of highly altered, bright green mafic rock.

Point 3-2 is the highest exposed knob of rock visible from the shore at 3-1. Selected features to be noted are:

From Point 3-1 - 3-3 excellently displayed graded bedding indicates that the succession is overturned. The coarsest basal part of graded beds are near 3-2, along the cliff edge, and these polymictic fine conglomerate beds have pebbles elongate N. 20°W.; plunging 25°. This direction may represent elongation parallel to the F_1 fold axis as this is the general trend of F_1 axes nearby.

Faults of more than one age and other features are present:

a) 15 m west of 3-1 there is a late brittle fault (N. 30°E.; 70° NW) which, with its branches, can be traced along this traverse 3-1 to 3-2, and shows right lateral offset of 2 m. These late open faults are filled with broadly warped slickensided quartz veins.

b) About 20 m west and 30 m southwest of 3-1 earlier faults may be seen. Look for light colored tuffaceous rocks which show truncation of bedding. In each case the fault is marked by the presence of folded quartz veins. The dominant S_2 cleavage, showing transposition, crosses both faults without interruption and therefore the faulting is probably Late Precambrian or associated with the Avalonian or Cadomian II orogeny. The S_2 cleavage forming event, however, may be pre-Pennsylvanian Paleozoic in age.

c) An altered greenschist mafic sill (N. 43°W.; 18°NE) up to 1 m thick is well exposed 15 m N of 3-2, it has fine grained chilled margins against the enclosing sedimentary rocks.

d) Throughout this traverse the S_2 cleavage is refracted from low angles in the slaty beds to a higher angle, a modified S-shape, in the more competent sandy and tuffaceous beds.

3-3 - 3-4. The traverse continues over inverted graded beds to point 3-4, about 100 m NW of 3-2. Note that as you pass over a late, approximately E-W striking fault, marked by the presence of non-folded quartz veins dipping 20°- 30°N, the beds in these two craggy block ridges above the fault are upright, on graded bedding criteria, except in the F_1 fold described above.

3-4. On the western end of these blocks, however, a recumbent syncline of graded beds opens to the west. The axial plane strikes and dips N. 20°W.; 30°NE; and fold axis orientation is N. 15°W. at 6°). This is an F_1 fold since both limbs are cut by the S_2 cleavage. It may be a soft sediment fold upon which was deposited the upright sequence between 3-4 and 3-7.

The contact between the overturned and upright beds is about 4 m east of the above F_1 fold and its inverted limb is marked by a folded and lineated chlorite-quartz vein interpreted as an early fault. About 0.5 m above this fault is a soft sediment slump fold.

3-5 and 3-6. Point 3-5 is on the upper shore and is recognized by the presence of a folded green chlorite-plagioclase-quartz mylonite marking the fault plane between the upright succession (between 3-5 and 3-4) and the steeply dipping inverted beds north of this normal fault. Note that the graded sandstone and slate beds east of this fault (N. 30°W; 62°NE) form a truncated syncline abutting the fault on its north side.

At point 3-6, at the base of the prominent cliff, is a quartz vein breccia-filled fault (N. 35°E.; 35°NW). The fold at 3-4 plunges below this fault and is not seen north of its described locality.

3-7. This is along the cliff above 3-6 and along the western part of the exposed outcrop. There is a strong color and structural contrast between the maroon graded sandstones which are east of the contact exposed here and pale green to yellow tuff beds, the thin maroon siltstones, and dark green finely layered siltstones of the Graves Point member.

The latter units define an F_1 fold at this locality and a series of such folds between this locality, the Lighthouse (3-15) and beyond. Here the upright F_1 fold axis plunges 10° toward N. 10° E and its curved axial plane is overturned to the SE. There is a well developed S_1 cleavage in the nose of this fold in the maroon siltstone beds and it is cut by a well developed S_2 transposition cleavage and a thrust fault.

3-8. Trace this contact between the two sequences northward a few meters and note that the maroon graded beds are upright but that the other ("the green") sequence is inverted, both determined by excellently developed graded beds. Since the S_2 cleavage cuts both limbs of early folds and the Graves Point sequence appears to have a larger number of identifiable structures (as will be seen in later localities) we infer that the inverted green sequence may have undergone a deformational episode in which the maroon sequence of this stop was not involved.

3-9 and 3-10. Tracing the contact northward one encounters a gully (3-9) developed along a late quartz vein-filled normal fault (N. 30° E.; 60° NW) about 300 feet south of the lighthouse. The horizontal component of dextral movement is about 15 m. North of that fault both the maroon and green sequences are inverted and essentially conformable.

3-10. This point is located about 300 feet south of the lighthouse, east of the grassline bordering the shoreline exposures and just south of the trace of the fault at 3-9. Here one would expect to find the upright sequence. However, the beds pass from steeply overturned to vertical to shallow-dipping upright as traced from east to west. This has implications for interpretations of the large scale structure of this area.

3-11 to 3-15. The features of these stations are in the block north of the fault of 3-9. Station 3-11 is a convenient place to examine the stratigraphic succession of the Graves Point member in a confined area. North of this fault the entire shoreline outcrop area is dominated by F_1 folds and to a lesser extent by F_2 folds in this distinctive mixed green and maroon sequence.

This inverted sequence from older to younger, based on graded beds, is as follows:

Unit 1. Buff weathering gray lapilli tuff beds (0.5 m).

Unit 2. A few meters each of maroon siltstones and pale green to light gray phyllite and siltstones.

Unit 3. Maroon slates, siltstones, and graded sandstones.

3-12. An F_1 syncline about 15 m long, the core of which is composed of inverted tuff beds, is well defined by the contact with the brightly colored units below.

3-13. At this point and northward to the lighthouse (3-15), an altered mafic dike (N. 20°E.; vertical) cuts across these F_1 structures and is involved in F_2 folding. At locality 3-14 (near the grassline) and near the contact with a complex synclinal structure there is a series of faults which antedate the S_2 cleavage. Between this locality and the lighthouse there is a north plunging inverted F_1 syncline. The dike of 3-13 can be traced across this structure to the base of the Castle Hill Lighthouse where it, as well as thinly laminated maroon siltstones and slates in the cliff above the late fault, define well developed F_2 folds and associated S_2 cleavage.

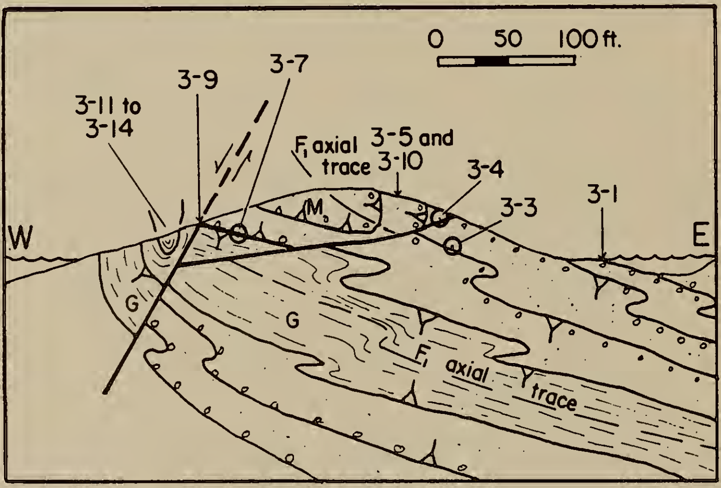

Figure 5. A composite cross section sketch showing the Castle Hill and Graves Point members of the Newport formation in a faulted overturned recumbent syncline at Stop 3. Points on the traverse are noted. Points on the traverse are projected into the plane of section. M beds are those of Castle Hill member and G are those of the Graves Point member.

Summary

On the basis of the above data from this locality and relevant data elsewhere on the Island we interpret the features described above as part of a major recumbent F_1 syncline cut by faults of several ages (Fig. 5). The maroon sandstone sequence makes up the Castle Hill member of the Newport formation and the green and maroon beds form the basal part of the Graves Point member or Brenton Point members.

Return to starting point by going south to Locality 3-10 and follow the path for a few hundred feet to the Cottages.

Retrace route and proceed northeasterly on Ocean Drive and Castle Hill Avenue for 0.2 miles; and follow Ridge Road for 0.8 miles to Harrison Avenue.

Mileage	
7.75	U.S. Coast Guard Station, Castle Hill.
7.85	Shamrock Cliff Oceanside Hotel and Restaurant on left.
8.0	Casey's Broadlawn Estate on left.
8.55	Road to Hammersmith Farm, the former home of Mr. and Mrs. Hugh D. Auchincloss, for a time the Summer White House during the Kennedy Administration.
8.8	Turn left at entrance to Fort Adams State Park. Continue past the gatehouse. Turn right at intersection at stop sign. Follow paved road downhill toward the shore past the parking lot near the picnic area on right.
9.15	Turn right at Fort Adams Beach.
9.25	Park near the boat ramp at the rear of the Park Bathhouse and Snack Bar, the former artillery stables, and walk along shore to the rock outcrops.

Stop 4. Olistostrome of the Fort Adams member of the Newport formation. Fort Adams State Park Beach.

The following are the more significant features of this locality:

A. The upper unit of the Fort Adams member is well exposed along the shore. This unit consists dominantly of greenish-gray weathering chlorite-feldspar sandstone up to 15 cm thick, and of buff weathering quartzite in part more vitreous than the green beds, both interbedded with maroon siltstone and phyllite beds typically less than 1-2 cm thick.

B. These rocks are polydeformed, in part as a result of processes acting contemporaneously with deposition of the sediments; and in part later tectonic deformation.

1. Although the sandstone beds can commonly be traced in plunging folds for a meter or for several meters, these beds are typically dismembered. This pulling apart of the more competent beds appears to have taken place by two processes: a) a soft sediment slumping or flowing of parts of the sandy beds, and b) by a quasi-boudinage type of extension parallel to the bedding, resulting in the distribution of dismembered layers and irregular shaped blocks and pieces of the more competent sandstone beds.

   In part the olistostrome consists of polymictic blocks which must have been lithified prior to their incorporation into the sedimentary succession. At this locality there are ellipsoidal blocks of gray vitreous quartzite, and buff-weathering dolomite each up to 8 m long (Fig. 6). The long axes of the largest blocks are about three times that of the other two dimensions.

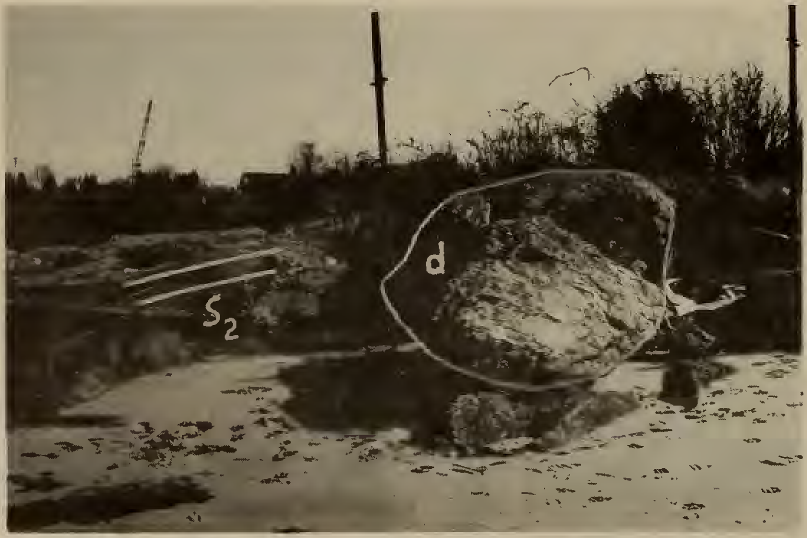

Figure 6. Fort Adams State Park Beach looking south-southeast at the Fort Adams olistostrome. In right foreground (d) is elliptical dolomite olistolith 8 X 2.5 X 2.5 m and the enclosing sedimentary rock crops out on left. Trace of S_2 cleavage is shown.

2. Two episodes of folding are recorded as F_1 and F_2. Graded beds in upright F_1 folds indicate that the beds young toward the east. These folds have an axial plane orientation N. 25°W; 60°NE; and the fold axis trends N. 8°W. plunging at 5°. These folds have been flattened to produce F_2 folds to which the dominant cleavage (N. 8°W; 22°NE) is axial planar. Walk northwest from the beach to the access road and go left around the corner for about 100 m along this main road. Examine these outcrops in the road cut between the beach and the picnic area with parking lot.

   Features of interest here include:

   The rock matrix is characteristically a deep green chlorite-muscovite-quartz schist rich in conglomerate particles of a wide range of sizes; boudinaged layers of vitreous gray quartzite, brown weathering ankeritic gray quartzite; and green chert pebbles and masses of chert separated by S_2 transposition cleavage planes. This lower unit of the Fort Adams member differs from the upper unit in that it is more difficult to trace bedding because the rock is characterized by transposition on the S_2 cleavage. Blocks of boudinaged quartzite typically have an S-shaped cross section viewed in sections normal to the trend of F_2 fold axes. Late, east-dipping brittle faults commonly are essentially parallel to the S_2 cleavage but some dip more steeply and cut the S_2 cleavage. Features in this outcrop are similar to those near the guardhouse on the access road from Ocean Drive to the Park. One of the boudinaged gray, vitreous quartzite blocks at that locality has two axial dimensions of about 5 X 12 m.

Retrace route to Harrison Avenue.

Mileage	
9.7	Go left (east) on Harrison Avenue.
9.8	Hammersmith Road on right.
9.9	Outcrops of Price's Neck volcaniclastics on north and south side of road and extensive outcrops of thick, well-graded turbidites may be seen in the rolling hills in the fields west of Edgehill Newport.
10.2	Pass entrance to Edgehill Newport on right.
10.25	Turn right on Beacon Hill Road and then immediately left at triangle formed by Beacon Hill Road and Brenton Road. Park and walk up hill 50 m.

Stop 5. Price's Neck formation, Unit 2. On west side of Beacon Hill Road 50 m south of junction with Brenton Road at Edgehill Newport.

At this locality may be seen graded tuff beds whose orientation is N. 87°E ; 90° and which face north. Well laminated horizons show strong soft sediment deformation and the development of S_2 cleavage with well developed elongation of thermal spots in the plane of S_2. Tiny slump balls are recognized on the glacially polished flat surface of this outcrop. The implication of the cleavage-thermal spotting is that the thermal spotting developed subsequent to the S_1 formation and prior to S_2.

On the east side of the road 100 m south of Stop 5 the S_2 cleavage is refracted and one may observe that the thermal spots are similarly refracted.

Mileage	
10.5	Pass Wickham Road on right continuing on Brenton Road.
10.7	At four corners go right on Harrison Avenue.
11.1	Harrison Avenue ends at Carroll Avenue. Take a right and immediately follow left fork (Carroll Avenue).
11.4	Recreation Park at Ruggles Avenue where Newport granite of a former quarry outcrops. Continue on Carroll Avenue.
11.95	Intersection with Ocean Drive. Go left (east) on Ocean Drive.
12.45	Ocean Drive ends at Bellevue Avenue. Turn right and follow Bellevue Avenue.
12.55	Turn right on Ledge Road.
12.8	Park along shoulder of Ledge Road. Note parking restrictions. Proceed to the shore and follow Cliffwalk along the shore to the east for approximately ½ mile to Doris Duke's property which can be recognized by barbed wire fence. Continue to contact of granite and sedimentary rocks.

Stop 6. Contact relationships of Newport granite with Fort Adams formation. Cliffwalk northeast of Ledge Road and to the east of the southern three mansions on Bellevue Avenue, (Fig. 7).

Significant geologic features here include:

A. The Newport granite and pegmatite are intrusive into the olistostrome of the Fort Adams member of the Newport formation. Thermally spotted sedimentary rocks of the olistostrome are recognized at or near each of the Localities 6-1 to 6-6. North of the latter locality rocks of the olistostrome are interbedded with volcanic and volcaniclastic rocks of the

Price's Neck formation and still farther north (Fig. 1) become the typical volcaniclastic rocks of Price's Neck formation.

In places the Fort Adams olistostrome has an abundance of volcanic debris and may be easily confused with agglomerates. However, its polymictic nature and the presence of intrusive fragments varying from ultramafic to granitic precludes such an interpretation.

B. Original sedimentation features include well developed sedimentary layering associated with subparallel S_1 cleavage and striking essentially E-W and is vertical; and the presence of blocks and fragments of great lithologic variety. As was the case also at Stop 4 in Fort Adams, stretching parallel to the bedding has given rise variously to boudinaged pods or blocks of more competent rocks which may be difficult to distinguish, as for example, the lenticular jasper at Station 6-3.

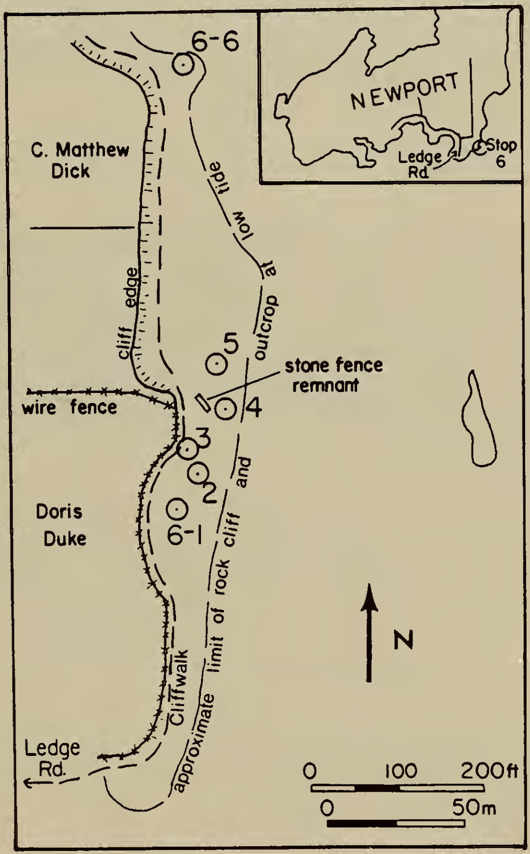

Figure 7. Sketch map of Stop 6, southern Cliffwalk, showing location of selected geologic features at and near the contact of the Newport granite with the olistostrome of the Fort Adams member of the Newport formation.

C. Structural features diagnostic of relative time of intrusion.

Earlier we noted that Smith (1978) had obtained a Rb/Sr whole rock age date of 595± 12 Ma. At several points of this stop one may observe granite and pegmatite cutting across the earlier formed S_1 cleavage in the sedimentary rocks but in turn are cut by the well developed S_2 cleavage (Fig. 8). Thus the intrusion of all phases of the Newport granite appear to have come in after the onset of deformation as evidenced by the S_1 cleavage but before the development of S_2. S_1 here commonly strikes approximately E-W but shows the variability that one expects from an earlier structure; S_2 commonly strikes in a northeasterly direction. There is additionally a strong mylonitic shearing and penetrative cataclastic deformation along the S_2 trend, as is well shown at Stations 5 and 6 (Fig. 9) respectively.

Specific features may be observed at the following localities:

6-1. Porphyritic granite cuts hornfelsed or "spotted" sedimentary rocks; associated pegmatite is traced back into the granite. Outstanding development of S_1 cleavage (N. 50°E.; steeply dipping) cut by granite and pegmatite (Fig. 8) and in turn are cut by S_2 (N. 10°E.; 45°NW).

6-2. Mafic dike well exposed on top of cliff.

6-3. Granite and border phase pegmatite cut across sedimentary beds. Only the latter are cut by S_1 cleavage (N. 80°W.; vertical) but granite, pegmatite and sedimentary rocks are cut by S_2 (N. 20°W.; 50°SW). Nearby the olistostrome contains polymictic fragments of coarse felsite, with lesser amounts of mafic rock. Boudinaged jasper veins and/or blocks are seen on the cliff edge; mafic dikes are stretched out parallel to S_1 cleavage.

6-4. Yellow-weathering gabbro blocks are present in the olistostrome. Just to the north of the remmants of a stone fence on the outcrop is a specimen of late mylonitic shearing, parallel to the granite contact (Fig. 7) and parallel to S_2 cleavage (N. 48°E; vertical) in the adjacent sedimentary rocks. East-West striking S_1 cleavage is deflected into the plane of mylonitic shearing. A xenolith (Fig. 9) and a relict xenolith, now largely granite, preserve the S_1 cleavage orientation of the adjacent sedimentary rocks. The curving of the sedimentary bedding and S_1 cleavage into the mylonitic shear zone indicates that the movement was dextral .

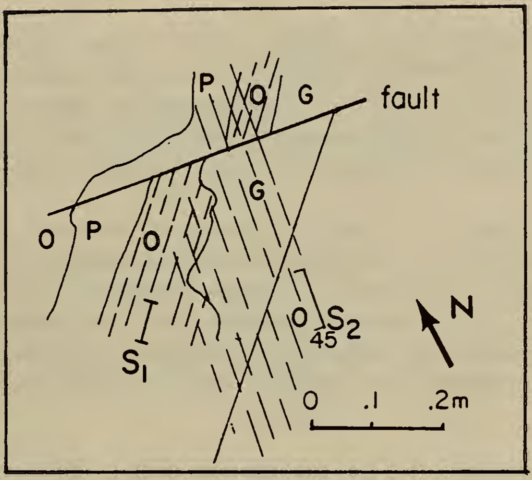

Figure 8. Sketch of an intrusive contact of the Newport granite (G) and pegmatite (P) cutting hornfelsed olistostrome of the Fort Adams member of the Newport formation (O) at Point 6-1 (Fig. 7) on Cliffwalk, Newport, Rhode Island. S_1 is first cleavage; S_2 is second cleavage.

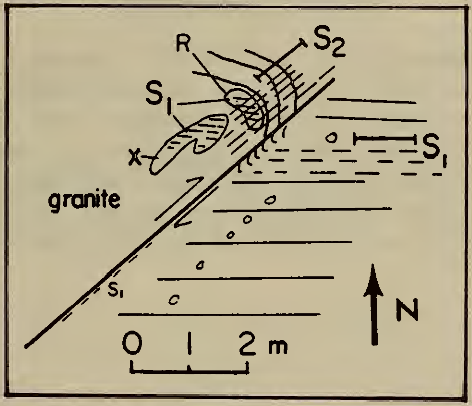

Figure 9. Sketch of a zone of dextral mylonitic shearing along the orientation of the S_2 cleavage. The xenolith (X) and relict xenolith (R) retain the S_1 cleavage.

6-5. Go north of the mylonitic shear zone across a prominent gully. Here there is a pervasive cataclastic deformation on the S_2 cleavage (N. 45°E.; 60°NW.). For example, about 6 m north of 6-5 a pegmatite is conspicuously cut from end to end by cataclastic features along the S_2 cleavage orientation.

6-6. The rock promontory in front of the Matthew and Ronald Dick mansion is a polymictic olistostrome including a block of jaspilitic quartz 1 m long. Closely spaced fractures (N. 10°W.; vertical), showing sinistral displacements, cut S_2 cleavage. If these are fractures related to the breakup of the Avalonian terrain they agree with the offset directions of Kent and Opdyke (1978).

Time permitting one may continue north for about ½ km and examine the transitional boundary between Fort Adams olistostrome sediments and the volcaniclastic and volcanic rocks of the Price's Neck formation well exposed along the shoreline. Where directions of tops of beds are known from graded beds they are consistently to the N and become easier to read toward the north.

Return to Ledge Road and go north along Bellevue Avenue following signs to Newport Bridge. Return to main routes via Route 138 west. If returning to University of Rhode Island, go west on 138 over the Newport Bridge.

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THE BLACKSTONE SERIES: EVIDENCE FOR AN AVALONIAN PLATE MARGIN IN NORTHERN RHODE ISLAND

Dreier, R. B., and Mosher, S.
Department of Geological Sciences
University of Texas at Austin
Austin, Texas 78712

INTRODUCTION

The Blackstone Series of Northern Rhode Island is a rare example of a well-exposed Avalonian terrane consisting of rock assemblages commonly associated with active plate margins. The series contains pillowed and massive basalt flows which are associated with mafic volcaniclastics, thin interbedded quartz-rich layers, gabbros ,and possible serpentine bodies. Other units in the series include conglomerates, limestones, and medium to coarse-grained, poorly sorted quartz arenites which have slumped into fine grained, pelagic(?) clastics. The series is bordered in part by granitic bodies which show intrusive contact and have been dated as Late Precambrian/Early Cambrian in age (see Hermes, Gromet and Zartman, this volume).

Type localities for the rock units are located near the Blackstone River in the Pawtucket Quadrangle which was originally mapped by Quinn et. al. (1949). Quinn divided the Blackstone into four members, with the normal stratigraphic succession being, from oldest to youngest, Mussey Brook Schist, Westboro Quartzite, (later changed to the Quinnville quartzite, Quinn, 1971), Sneech Pond Schist and the Huntinghill Greenstone. The latter included extrusive and intrusive igneous rocks as well as clastic sediments. Reconnaissance work done by Mosher and Wood (1976) and Robare and Wood (1978) suggests that much of the Blackstone Series is a tectonically induced sedimentary melange. This article presents preliminary work from part of the first author's Ph.D. dissertation.

LITHOLOGIC UNITS

Each member of the Blackstone Series contains a wide variety of lithologies which are often similar to those in other members. This apparent similarity of portions of individual members is caused, in part, by syn-depositional mixing of the "members" and post-depositional interformational folding. The present study has each different type of lithology mapped separately rather than grouped into members. For the purpose of disscussion, the lithologies have been divided into three general catagories: greenstones, clastics, and carbonates.

Greenstones

The Huntinghill Greenstone contains mafic volcanic flows and volcaniclastic sediments. The flows are often pillowed with carbonate filling the interstices. Many massive flows show relict pillow structures. The flows are associated with rare occurances of gabrro and serpentine; the latter contains relict cores of olivine and pyroxene (Quinn et. al., 1949).

The volcaniclastics are mafic, fine grained thinly laminated sediments which are difficult to distinguish from flows in the field. Locally epidote-rich pods (up to a meter in diameter) and stringers parallel the prominant schistosity. Few, thin, pure quartz layers are interbedded with the volcaniclastics and possibly represent relict chert beds; however quartz recrystallization has obscured any initial sedimentary texture. Felsic volcanics are only present at one locality in a fault sliver which separates mafic flows from volcaniclastics.

Clastics

Quinn (1949) originally divided the clastic sediments into three separate units: Mussey Brook Schist, Quinnville Quartzite, and Sneech Pond Schist. New exposures along Highway 295 and in quarries bordering the Blackstone River suggest that only two units should be distinguished.

One unit is dominated by quartz-poor, mica-rich schists and interlayered, pure quartzites. The schists show no graded or cross bedding; laminations are rare. The quartzites are composed of poorly sorted, subrounded grains; layers range in width from meters to 10's of meters. Rarely quartzites occur as small pods or lenses. The quartzites show many characteristics of soft sediment slump blocks in a muddy matrix. These characteristics include: elongate "teardrop"-shaped lenses with mud armoring of the rounded ends and mixing of sand and mud within the sand body margin; "pull-a-part" structures; mud armoring of small semi-spherical quartzite pods; local, irregular thinning and thickening of layers; and "jiggle" structures where sand blocks have been slightly pulled apart into small pods and the fractures infilled with wispy mud

The other unit is a dark, quartz-rich schist containing conglomerates which increase in abundance and clast size to the south. Quartzite slump blocks are sometimes present. Mafic flows intrude these units and are found as clasts within the conglomerates.

Carbonates

Marble layers are located throughout the area but the largest are situated in the southwest. The marbles are in depositional contact with the quartz-rich, medium grained, dark sediments, and are intruded by mafic and granitic dikes and granodiorites. Two possible origins for the marbles are suggested: 1) shallow marine deposits which have subsequently been slumped, or 2) deep water limestones which are overlain by clastics containing slumps of shallow water sediments.

STRUCTURE

Post-deposition deformation includes at least two episodes of folding and a low angle thrusting. The first recognizable deformation resulted in isoclinal folding and the prominant schistosity (S1). The schistosity is subparallel to bedding (So) which is defined by layers of quartzite and fine laminations in the volcaniclastics. Few F1 folds have been observed in outcrop, however the map pattern is suggestive of large scale interformational folding. Mineral lineations oriented N14E and plunging 40 NE may parallel F1 fold axes as they are contained in S1 and are folded by the second folds. Shear zones are subparallel to S1.

The second event folds the prominant schistosity and bedding into large recumbent folds. Generally this folding is only observable on a regional scale, however in a quarry in the NW portion of the area excellent exposures show several of the different lithologies folded together by recumbent folds on all scales. (Access to the quarry is not permitted by owners.) An axial planar crenulation cleavage (S2) is locally developed. Crenulation axes and a second mineral lineation (on S1) parallels the F2 fold axes. Another crenulation of S1 is shallower and appears to be younger than S2.

METAMORPHISM AND INTRUSION

The Blackstone Series has been metamorphosed to upper greenschist facies. Mineral assembleges in the mafic units include epidote, green amphibole, chlorite, quartz, biotite, and albite; garnets are found in the epidote-rich pods. The quartzites contain minor amounts of chlorite, muscovite, and biotite. The schists are dominately composed of muscovite and biotite; the cement in the quartzites contain chlorite, biotite, and muscovite. Generally, chlorite and biotite are elongate parallel to F1, however, the biotite also is observed in a random orientation as is the muscovite. A metamorphism is therefore believed to have begun during D1 but culminated post D1.

Granitic plutons have intruded the Blackstone either pre- or syn-tectonically. Near contacts, the granitic rocks contain two foliations, a mineral lineation subparallel to F2 fold axes, and small scale folds. The grain size of Blackstone units increases with proximity to the intrusion, and marbles show mineralogical evidence (fosterite and diopside) of contact metamorphism (Quinn and Young, 1937; Quinn, 1971).

AVALONIAN TECTONICS

The Blackstone series has been tentatively correlated with other terrains bordering the North Atlantic (Wood, 1974; Rast et. al., 1976). In North America, these terrains have been termed Avalonian, after the Avalon Penninsula in Newfoundland which contains extensive late Precambrian exposures (Kennedy,1976; Rast et. al., 1976; Strong, 1979; Rast, 1980). Other late Precambrian terrains are found along the Virginia-North Carolina border (Glover and Sinha, 1973; Snoke et. al., 1980), in Rhode Island rimming the Narragansett Basin to the east and south (Skehan and others, 1978; Skehan and Rast, this volume), and in eastern Massachusetts, Maine and Nova Scotia (Schenk,1971, 1980), Angelsey (Wales) (Wood, 1974), and in the English Midlands (Rast et.al., 1976; Rast, 1980).

In general these terrains are characterized by thick volcanic and volcaniclastic sequences locally interbedded with other sediments. Some deformation is pre-Caledonian and late Precambrian granitic intrusives are common. Locally these provinces are underlain by either gneissic or sedimentary basements. Avalonian rocks are generally considered to be of island arc affinity, but have been variously interpreted as originating in back arc or fore arc regions.

The Blackstone series was deposited in a marine environment as indicated by the pillow basalts, fine grained clastics, probable cherts, and carbonates. The lack of felsic volcanics, the mafic composition of the volcaniclastics, and the intrusive contact of the basalts and volcaniclastics suggests that volcanism may be due to rifting of oceanic crust. The quartzites and conglomerates are of continental origin. The presence of sedimentary slumping of the quartzites and the complex intermixing of all units within the Blackstone suggest that much of the series comprises tectonically induced sedimentary melange.

Presence of oceanic rifting, continentally derived sediments, and active syndepositional tectonism and lack of felsic volcanism support an active back arc basin model for the origin of the Blackstone series. This is a tentative interpretation and other possible models cannot be ruled out at this time. Further mapping and geochemical work is in progress to help further define the tectonic setting of the Blackstone in an attempt to determine its relationship to the other Avalonian terrains. The relationship of deformation and metamorphism in the Blackstone Series to other Appalachian events has not yet been determined.

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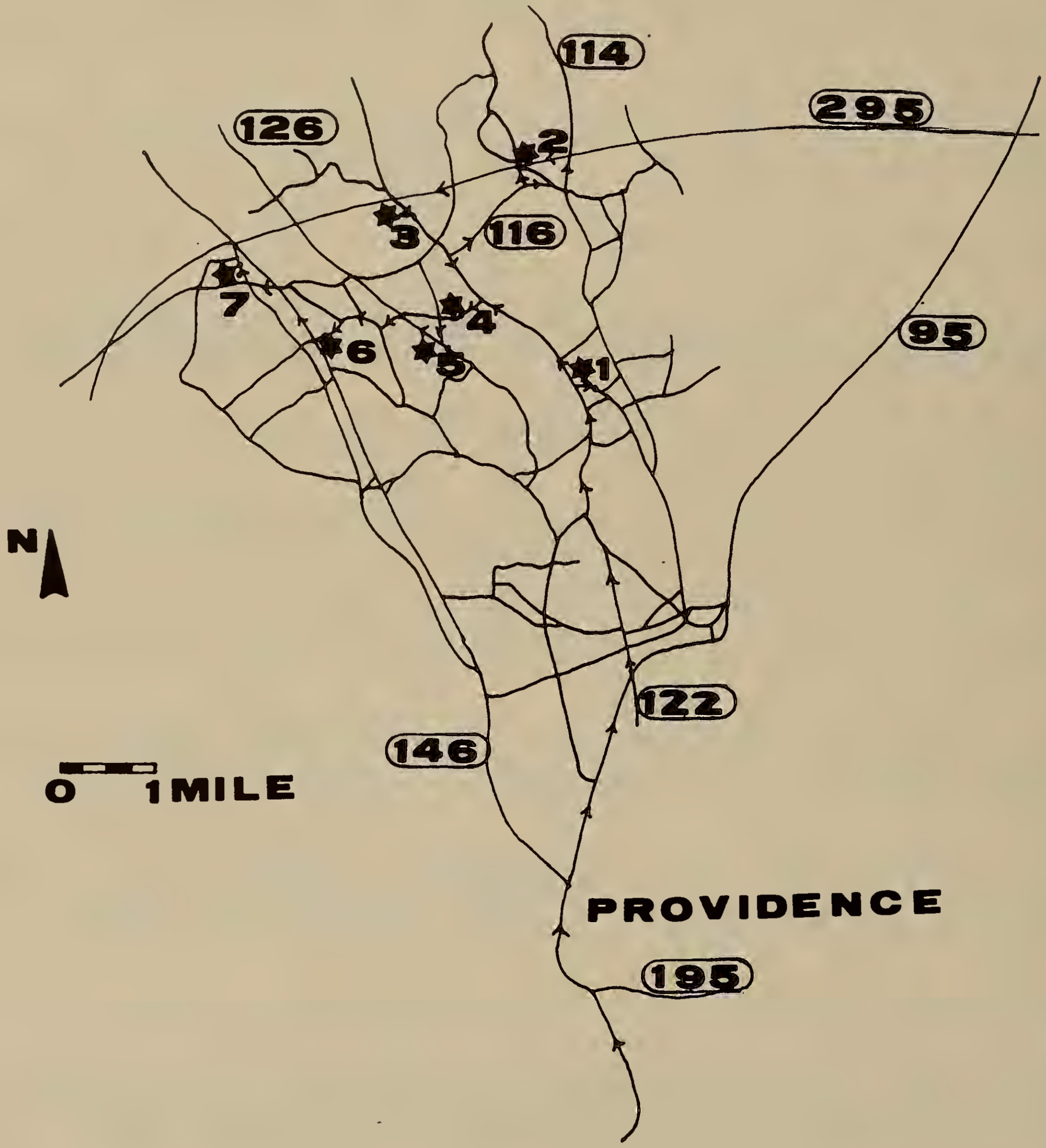


Fig. 1. Road map showing the route; stops are indicated with stars.

STOPS

Mileage	
	From Kingston take Rt 138 east to Rt 1. Turn left and follow Rt 1 and signs for Providence. You will take Rt 4 north to Interstate 95. Take Interstate 95 through Providence.
0.00	Take Exit 26 (Lonsdale Ave, Main Street, Rt 122) off Interstate 95 . Follow signs for Rt 122, you will pass one stop sign, then two traffic lights, and cross over the freeway.
0.75	Turn left onto Connant St.
0.80	Turn left at next traffic light onto Mineral Springs St.; pass a cemetary on the right; then cross over a railroad bridge.
1.10	Turn right at next traffic light onto Lonsdale Ave. Go north on Lonsdale Ave. Pass 3 traffic lights, a large pond on the left, another traffic light.
4.10	Turn right on Broad St. just past Almacs.
4.25	STOP 1. Dandurand Florist Shop. The prominant roadside ledge directly east of the flower shop provides the best exposure of relatively undeformed pillow basalts in the area. The pillows are ellipsoidal with average long dimension of approximately 45 cm. Vesicles in the pillows are elongate subparallel to S1 with long dimensions ranging from .5 to 2 mm. Vesicles and interstices between pillows are commonly filled with calcite. Bedding as defined by the pillows is right side up. Low angle shear zones are found in the lower eastern part of the outcrop, and the pillow shapes are no longer discernable. These shear zones are cut by high angle faults showing small displacements. A small outcrop of gabbro is found in a back yard to the north of this outcrop.
4.35	Return to Rt 122 and turn right at the traffic light. Behind the American Legion are outcrops of volcaniclastics in contact with the pillow basalts.
5.90	Roadcuts are of quartzites and schists.
6.55	Turn right onto Rt 116 North (Angel Rd.) passing outcrops of quartzite and schist.
7.45	Front yard to left has gabbro outcrop. 0.1 miles further are basalt outcrops.
7.7	Turn left at sign for Lippitt Estates.
8.05	Cross under Interstate overpass and park.
	STOP 2. Roadcut along Interstate 295. Excellent exposures of the Huntinghill Greenstone. Across the road from where the cars are parked and at the eastern end of the outcrop on Hwy 295, the greenstone has been intruded by granodiorite. Continuing to the west is approximately 10 m of massive, deep blue-gray metabasalt flows. In thin section these very fine grained rocks are chlorite- and amphibole-rich with rare relict plagioclase phenocrysts.

Most of the rest of the roadcut is dominated by very fine grained, blue-black mafic volcaniclastics which locally show layering. Included in the volcaniclastics are epidote-rich thin stringers and lensoid pods which parallel the prominant schistosity and increase in abundance to the west. The larger pods are rich in garnet, clinopyxonene, calcite, and minor amphibole; some pods have calcite- and/or quartz-rich centers.

Intruding the volcaniclastics are at least two dikes with a distinct layered texture. The dikes are folded and their attitude varies from sub-horizontal to subvertical (one rims a prominant west facing ledge). In the central portion of the road cut (to the west of major joint faces in a narrow overgrown break in the outcrop), a narrow high angle fault zone, containing brecciated felsic volcanic material, separates volcaniclastics with epidote-rich stringers to the east from a massive non-layered flow to the west.

Approximately 25m from the west end of the outcrop are two diabase dikes which intrude the greenstone. The dikes are altered but undeformed. Sediments between and to the east of the dikes are isoclinally folded. Locally, thin quartzite layers (possibly chert) are interbedded and infolded with fine-grained volcaniclastics.

8.30 Turn around and return to Rt 116 and turn left.
8.50 Turn left onto Rt 114 North; follow signs for Interstate 295 South.
8.80 Take 295 South. Immediately on the left is a granite outcrop. Next you will pass the outcrops from Stop 2.
10.35 Take Exit for Rt 122. (You pass through Stop 3 outcrops in the interchange.) Turn left on Rt 122 South, and make a left into the Burger Chef parking lot (0.3 miles).

Stop 3. Road cuts on exit ramp show good three dimensional exposures of the first clastic unit (quartz-poor, mica-rich schists interlayered with quartzite lenses). This unit displays soft sediment slumping features (see text for description) as well as later tectonic deformation. In the schists the prominant S1 schistosity is crenulated by a shallow crenulation and rarely a steep one. Some of the boudinage of the quartzite layers appears to be tectonic. Geometric analysis shows that this area is on the overturned limb of a regional scale F2 fold. (The other limb is exposed to the west across the Blackstone River on Hwy 295.)

LUNCH STOP. Across the highway from the Burger Chef are some small (1m) outcrops of schists which contain isoclinal folds, two crenulations, and the southern end of one of the largest quartzite slump blocks.

11.30 Turn left onto Rt 122 leaving the parking lot. Pass one traffic light.
12.35 Turn right at next traffic light.
12.60 Before railroad tracks, turn right into paved parking lot. Walk back up hill to fenced parking lot. Turn right and follow fence line to outcrop on far side of lot, next to quarry.

Stop 4. This stop contains the same units as stop 3. Here the soft sediment deformation features are well exposed on a glacially scoured surface.

12.65 Turn right out of parking lot and cross railroad tracks and bridge.
12.95 Curve right to stop sign. Take sharp left at stop sign and go up

hill.

13.00 At Y intersection bear to left.

13.25 At stop sign turn left and then immediately right into blasted area. Park.

Stop 5. Dexter Road. The complex intermixing of the different lithologies are exposed in the three northwest trending hills. Parts of these hills have been blasted so that some outcrops are not completely in place, however movement has not been sufficient to disrupt the stratigraphy. The northern outcrop contains a matrix-supported conglomerate with rounded quartzite clasts which are locally brecciated. The conglomerate is in gradational contact with a mafic flow, which is pillowed on the northwest side. Calcite as veins and interstitial material between pillows is common.

A small outcrop to the east of the central hill is composed of fine-grained, quartz-rich sediments which contain a mafic-flow clast. The northwestern portion of the central outcrop consists primarily of conglomerate. Here clasts appear sheared, and are in a matrix of volcaniclastic material similar to that of Stop 2. Southwest of the conglomerate at the edge of the outcrop, a thick calcite vein or a limestone clast is surrounded by a mafic flow. Here mafic flows (or volcaniclastics?) interfinger with fine-grained, layered clastic sediments. No conglomerates are found.

The southeastern portion of the southern outcrop consists of fine-grained, quartz-rich sediments which contain rare purple chert clasts and are cut by thin tightly folded quartz veins. In the northwestern portion of the outcrop, the sediments interfinger with mafic material.

13.40 Return to road and turn left; bear left onto Old River Rd.

14.10 Turn left on Simon Sayles Rd before tall silo.

14.40 Turn right at stop sign.

14.90 Bear left onto Wilbur Rd and turn into Conklin's Quarry (0.3 miles).

15.2 Stop 6. Limerock. The largest marble exposures are in three N50W trending quarries. We will look at the southern quarry, first on the northeastern side and then at the bottom on the southwestern side.

The southeastern side of the quarry shows a depositional contact between marble and dark, quartz-rich, laminated sediments. Locally there is a thin band of pure quartzite at the contact. The sediments immediately overlying the contact contain small quartzite clasts which are possibly slump blocks. The sediments are in intrusive contact with a granodiorite (at the far eastern exposure) which shows little deformational fabric. At the northwestern exposure of the marble/sediment contact, the marble appears frothy, iron-rich and is slightly brecciated. This is probably due to hydrothermal activity. On the west facing slope behind the contact, the sediments are cut by vertical strike slip faults. Further to the north a mafic flow is in fault contact with a sheared granodiorite.

Go to the southwestern margin for an excellent view looking across the quarry at the depositional contact. Note the mafic and granitic dikes which occur parallel to the vertical faults previously mentioned and the lack of offset of the contact by the faults. Walk along the road at the southern part of the quarry; Granodiorite is intrusive into quartziorite, and both units contain two foliations planes. On the southern side of the road the quartz diorite is sheared. Between the igneous units and the marble is an iron-rich chert breccia and more frothy marble. Contacts are not exposed.

Going northwest into the quarry, the road is lined on the east by hydrothermally altered marble. Further north on east facing slopes (close to where the road is being blasted) is a brecciated intrusive contact between granodiorite and marble. Float from this blasted region shows granodiorite intrusive into both marble and volcanics. On the top of the dump pile, the contact is again sheared. It is probable that the southwestern border of the quarry represents a shear zone. The similarity of units on both sides of the quarry suggests that the marble is in the nose of a tight fold.

15.20 Turn back onto Wilbur Rd and cross the first bridge overlooking a marble quarry. Immediately turn right and go down a steep entrance ramp onto Rt 146.

16.10 Take Exit for Rt 116 South, the Lincoln Mall exit. (Also for North Central State Airport.)

16.80 Follow Rt 116. Turn right into Lincoln Mall at traffic light. Park next to McDonalds.

17.00 Stop 7. Lincoln Mall. The exposures are to the west of the mall along the road next to McDonalds. Mafic material, quartz-rich sediment, and fine-grained granodiorite (similar to that at stop 6) are interlayered and tightly folded (axes trend NS and plunge 26N). Behind the mall along the northern end of the parking lot, quartz diorite outcrops. The eastern exposures are intensely sheared and contain many dark, medium-grained xenoliths. The grainsize of the quartz diorite increases to the west where it been deformed by low angle (NW, 24NE) shear zones. The contact between the quartz diorite and Blackstone Series has undoubtably been reactivated as a shear zone.

---END OF TRIP---

IGNEOUS ROCKS OF NORTHERN RHODE ISLAND

Malcolm J. Rutherford and Michael R. Carroll
Department of Geological Sciences
Brown University
Providence, Rhode Island 02912

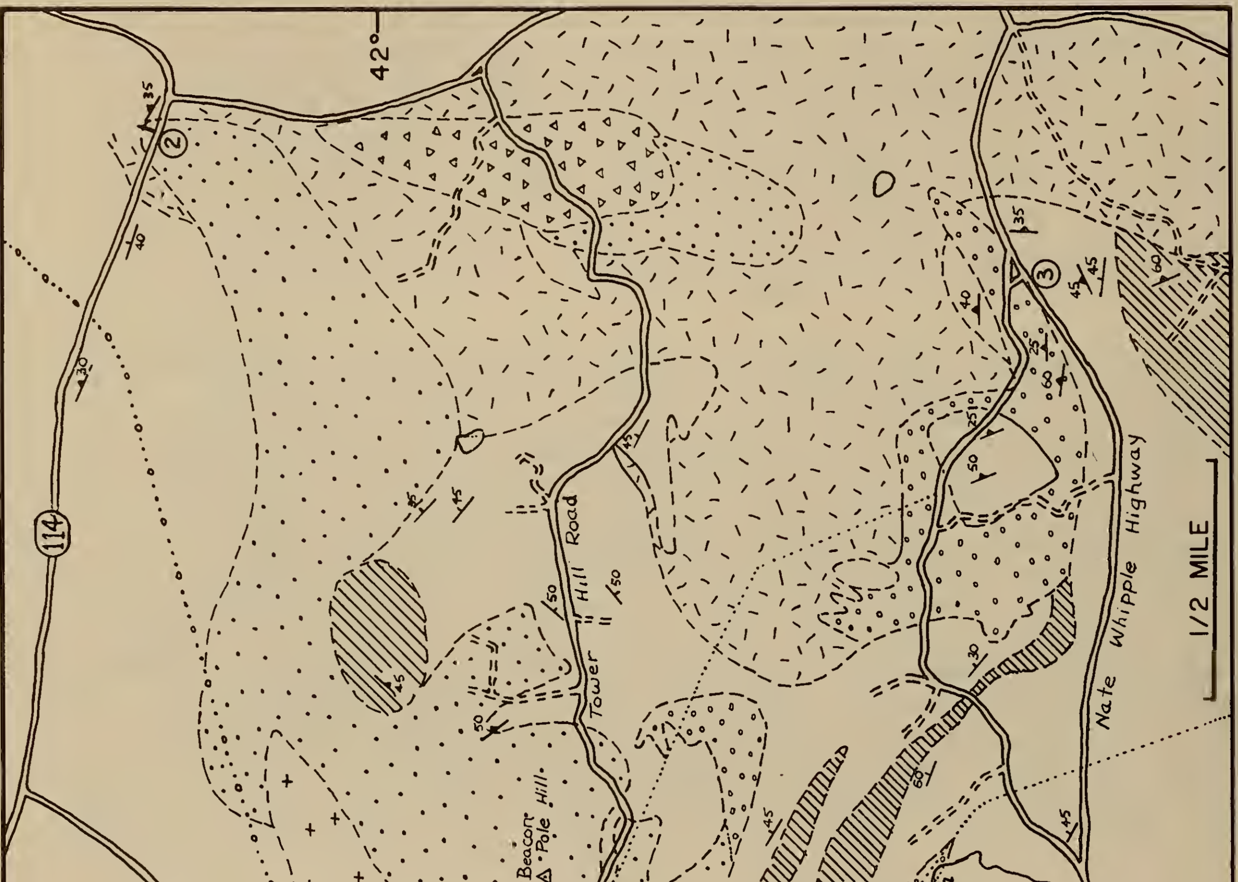
INTRODUCTION

The purpose of this field trip is to look at the field relations and associated data which have been collected for two igneous complexes exposed in the northern part of the Pawtucket Quadrangle (Quinn et al., 1949) Rhode Island (Fig. 1). The first complex which will be examined consists of an anorthositic gabbro and a magnetite-rich melatroctolite (Cumberlandite). Although the contact between these two rocks is not exposed (Fig. 1), a combination of mineralogical, geochemical and structural data appears to demonstrate a clear petrogenetic relationship. The second group of rocks which will be examined is a series of peralkaline granites exposed in the same general area. Quinn et al. (1949) tentatively correlated these rocks with the Quincy, Mass. Granite. Studies of the granitic rocks in this area are still at an early stage, hence there are many interesting questions and relatively few answers at this time. The igneous rocks of intermediate age (Esmond Granite, Grant-Mills Granodiorite) will also be seen at some stops.

REGIONAL GEOLOGY

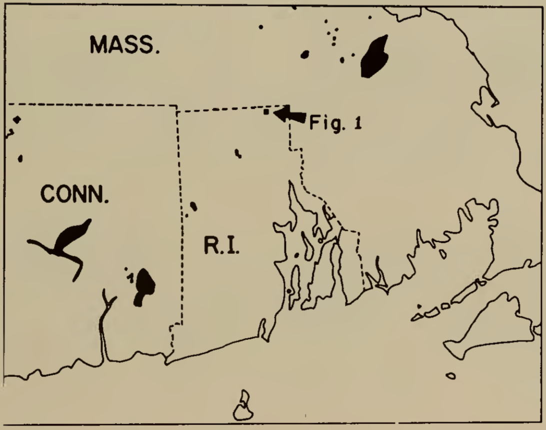
The oldest rocks in the Cumberland area are the Sneech Pond Schist and Hunting Hill Greenstone formations of the Blackstone Series (Quinn et al., 1949; Quinn, 1971) as shown in Fig. 1. The exact age of these rocks is not known, but available evidence favors a Precambrian rather than a Paleozoic age (Quinn, 1971; Rast et al., 1976; Robare and Wood, 1978). The Sneech Pond Schist is composed predominantly of quartz-mica-feldspar schists and quartzites with minor pebble beds and sills and dikes of Hunting Hill Greenstone lithology. The Hunting Hill Greenstone is predominantly a mafic volcanic sequence with numerous pillowed basalts. Interlayered with the mafic volcanics are minor amounts of lithologies characteristic of the Sneech Pond Schist. Locally, as on the hill east of Sneech Pond (STOP 4), there are thin calcareous horizons in the Hunting Hill Greenstone.

The Anorthositic Gabbro-Melatroctolite Igneous Complex appears to be the oldest of the igneous rocks which intruded Blackstone Series. Inclusions of the latter occur in the anorthositic gabbro along its northwestern margin. The anorthositic gabbro has in turn been affected by a


42°
114
122
Meeting House Rd.
Tower Hill Road
Beacon Pole Hill
West Wrentham Road
Sneech Pond
Nate Whipple Highway
1/2 MILE
N
1a
1b
1c
1d
2
3
4

LEGEND

Triassic (?)	▰	Diabase Dikes
SIL (?)	∘	Per-Alkaline Granite Porphyry.
	•	Per-Alkaline Granite. Microperthitic feldspar, aegirine and riebeckite granite.
Early Plutonic Series Precambrian or Early Paleozoic	+	Esmond Granite. Two feldspar, biotite granite.
	⁄	Grant Mills Granodiotite. Porphyritic.
	△ ▽	Quartz Diorite.
	∧ ∨	Anorthositic Gabbro.
	▱	Magnetite-rich Melatroctolite.
Blackstone Series PC	▨	Hunting Hill Greenstone. Basic volcanics with minor quartzo-feldspathic schists and marble.
	☐	Sneech Pond Schist. Quartzo-feldspathic schists and pebble beds; minor basic volcanics.
	——— - - -	Contact, dashed where approximate.
	—┴—	Compositional banding of sedimentary or igneous origin.
	—▲—	Foliation, strike and dip.
	··········	Power transmission lines.



Location Map for
Figure 1 (opposite)

deformation event which produced prominent shear zones throughout the gabbro, particularly along its margins. A massive plug of Esmond granite has been found in one of the shear zones. This observation has been interpreted as indicating the Esmond Granite is younger than the anorthositic gabbro (Rutherford and Hermes, MS).

The Esmond Granite is a massive to gneissic, two feldspar, biotite granite in which the original biotite and feldspar have often been partially altered to a fine-grained assemblage rich in chlorite and epidote. The age of Esmond Granite has not been determined radiometrically. Quinn (1971) states that the Esmond appears to grade into the Grant Mills Granodiorite and is intruded by the Quincy granite in the Pawtucket Quadrangle. This observation indicates the Esmond could be late Precambrian or Early Paleozoic. The latter constraint comes from the correlation of the peralkaline granite in this area with the Quincy Granite in Massachusetts, which is thought to have been emplaced at about 420 m.y.b.p. (Naylor and Sayer, 1976).

The two types of peralkaline granite, the equigranular and the prophyry (Fig. 1), both have a foliation which appears to have developed after the rocks crystallized. In places there is also a flow banding or flow lineation in the same rocks. The tectonic foliation resulted from a deformation event that affected rocks in the area sometime after the emplacement of the peralkaline granites, but prior to the emplacement of a series of north-trending diabase dikes. The unmetamorphosed diabase dikes (STOP 2) have been correlated with the Triassic diabases and basalts (Quinn, 1971) found throughout the state.

THE MELATROCTOLITE-ANORTHOSITIC GABBRO COMPLEX

General Petrology and Structure

The melatroctolite is a black, dense (S.G. = 4.0) massive to weakly laminated rock exposed in a small area (Fig. 1) at the north edge of the Pawtucket Quadrangle (Quinn *et al.*, 1949; Rutherford and Hermes, MS). It is an impressive looking rock composed of olivine (49%), titaniferous magnetite (32%), large (2 cm) tabular plagioclase (15%), and minor ilmenite and Al-rich spinel. The plagioclase in the melatroctolite tends to have a preferred orientation which produces the weak foliation in the rock. Although the nature of the minerals and textures indicate the rock is probably igneous, the rather unique modal composition raises questions about how such a rock originates. In the latest work done on the melatroctolite, Johnson and Warren (1908) arrived at no acceptable theory for the origin of the rock, although they did conclude that the melatroctolite and anorthositic gabbro might "be offshoots from a common magma".

The relationship between the melatroctolite and the adjacent anorthositic gabbro was not known at the time this work began (Rutherford and Hermes, MS). The contact between the two rock types is not exposed and the two closest outcrops are 1000 feet apart. Inclusions of gabbro have been found in the melatroctolite, but while some have sharp and angular boundaries (Fig. 2b), others have very irregular outlines and look like large (10 cm) aggregates of cumulus plagioclase. Macroscopically the melatroctolite and gabbro look quite different, but the same minerals occur in both rocks; only the modes (and the bulk compositions) are different. The two rocks are also similar in that both appear to have an igneous lamination, although it is much better developed in the gabbro (Fig. 2c). The following sections review the results of a study of the mineralogy and petrology of the melatroctolite and anorthositic gabbro carried out (Rutherford and Hermes, MS) to determine the origin of the rocks.

Mineral Chemistry

The anorthositic gabbro and melatroctolite have been sampled extensively and the minerals analyzed with the electron microprobe. The minerals in the melatroctolite are completely unzoned; the plagioclase is $An_{59}Ab_{30}$, and the olivine is Fo_{64}. The large ilmenite and titaniferous magnetite grains in the melatroctolite were also analyzed. The ilmenites are homogeneous, but a wide beam technique was necessary in analyzing the titaniferous magnetites because of the microscopic exsolution and oxidation (Fig. 2d and 2e). The compositions of the large grains ($Ilm_{94}Hm_6$ and $Mt_{26}Ulv_{63}Hc_{10}$) yield temperatures of $950^\circ C \pm 100^\circ$ and an f_{O_2} of $10^{-12.5 \pm 1.0}$ using Lindsley's (1977) data. The large error bars on these values are primarily the result of the large hercynite component in the spinel phase.

The euhedral, tabular (1 cm x 1 mm) cumulus plagioclase crystals in the gabbro have exactly the same composition as the plagioclase in the melatroctolite, An_{59}, but they have intercumulus overgrowths which range from An_{60} to An_{40}. Other cumulus phases in the gabbro are olivine, ilmenite and titaniferous magnetite (See Fig. 2c and Fig. 4). Very few unaltered olivines were found in the gabbro and most were embayed and obviously in reaction relation with the Ca-rich pyroxene. The few olivines that were suitable for analysis were unzoned and ranged from Fo_{54} to Fo_{40}. The titaniferous magnetite and ilmenite were $Mt_{21}Ulv_{70}Hc_9$ and $Ilm_{95}Hm_5$ respectively, which is very close, although not identical to those found in the melatroctolite. The pyroxene in the gabbro appears entirely intercumulus and has a composition $En_{34}Wo_{48}Fs_{17}$. There is also minor late hornblende and apatite in the gabbro, and they, like the pyroxene, are not present in the melatroctolite.

Whole Rock Chemistry

Four samples of the melatroctolite and ten of the anorthositic gabbro have been analyzed using a combination of wet chemical and atomic

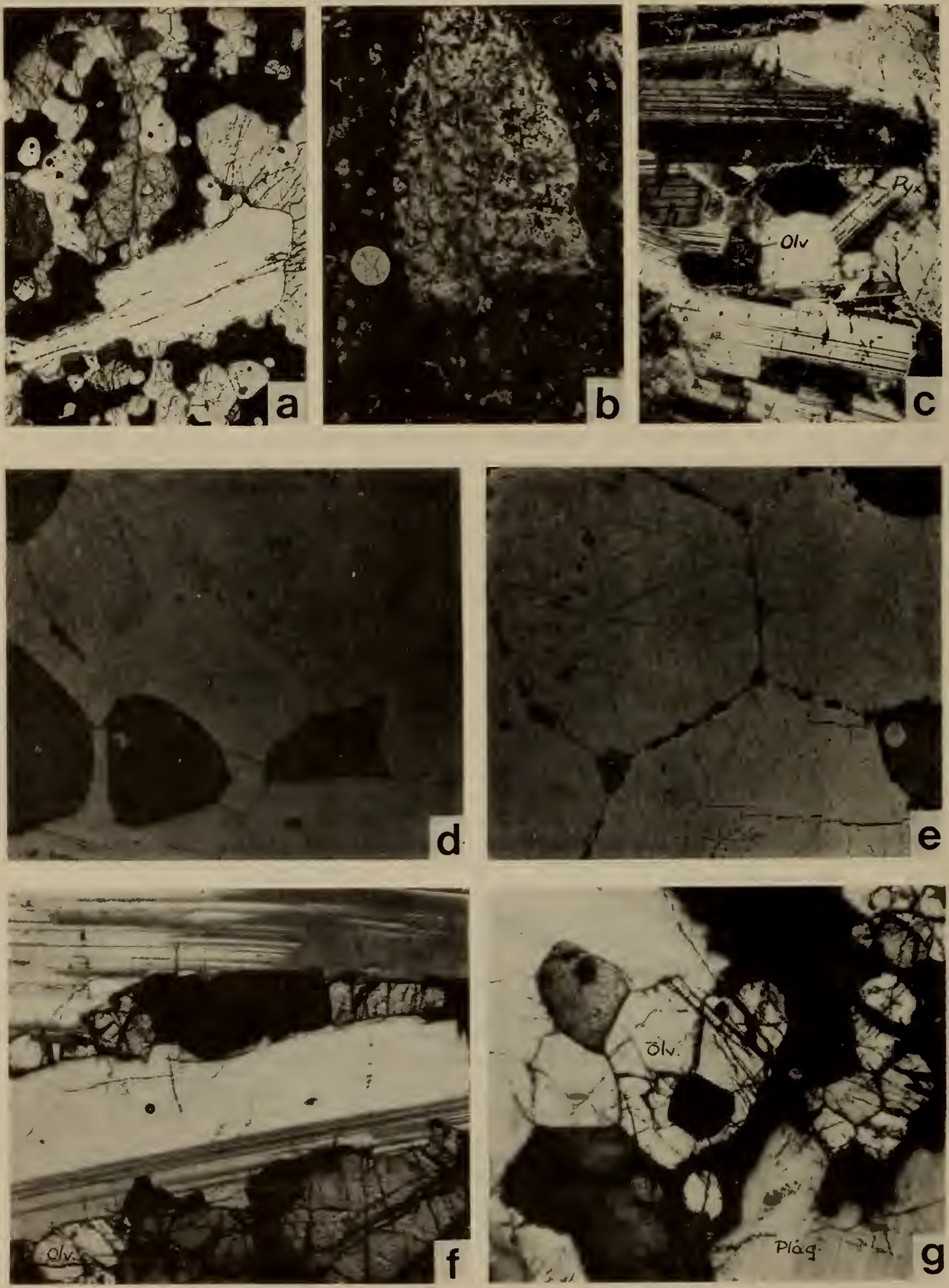

a
b
Pyx
Olv
c
d
e
Olv.
f
Olv.
Plag.
g

Figure 2

2A: Melatroctolite, plane light, tabular plagioclase aggregate is 2 cm long. Note intergrowth of grains along their margins and apparent interstitial nature of Fe-Ti oxides.

2B: Anorthositic gabbro inclusion in melatroctolite. The only pyroxene in the melatroctolite is in these inclusions. See text for explanation.

2C: Anorthositic Gabbro, crossed nicols. Longest plagioclase is 1 cm. Cumulus minerals are plagioclase, olivine and titaniferous magnetite; intercumulus minerals are Ca-rich pyroxene and plagioclase.

2d and 2e: Melatroctolite in reflected light. Field of view is 4 mm wide. Titaniferous magnetite has exsolved aluminum spinel along (100) and ilmenite (exsolution and oxidation) along (111). Some movement of aluminum spinel from magnetite rims to grain boundaries has occurred. Note apparent 120° intersections between grains of Ti-magnetite, ilmenite and olivine.

2f: Melatroctolite in crossed nicols, transmitted light. Field of view is 2 mm. Note intergrowth of olivine and plagioclase and also olivine and Ti-magnetite included in plagioclase aggregate.

2g: Melatroctolite, transmitted light, crossed nicols. Field of view is 3 mm. Note 120° angle of intersection between adjacent olivine grains.

absorption techniques (Rutherford and Hermes, MS). The results of these analyses are shown in Fig. 3 where the major oxides are plotted versus Al_2O_3. Several of the gabbros are chemically identical, and only the six different analyses are plotted in this diagram. The Al_2O_3 of the gabbros ranges from 19% wt% in WG-14 to 25% in the more plagioclase-rich gabbros. Until recently WG-14 was considered to be a good chilled margin sample, but we are now studying a new sample (STOP 1d) which texturally looks like a better candidate.

The average and range of the four samples of the melatroctolite analyzed are also plotted on Fig. 3 (5.6 wt% Al_2O_3). The lines of Fig. 3 have been drawn from the average melatroctolite through the data for the gabbros for each of the oxides. The lines qualitatively illustrate the model that we have developed for the origin of these rocks. This idea, which is discussed more extensively below, is that the separation of the melatroctolite from a parent magma something like WG-14 (19% Al_2O_3) would produce a range of more Al_2O_3 rich rocks such as the anorthositic gabbros.

Origin of the Melatroctolite and Anorthositic Gabbro

The structures, mineral textures, mineral chemistry and whole rock chemistry indicate that the melatroctolite and associated anorthositic gabbro can most logically be interpreted as the crystallization products of a relatively common magma, one having an anorthositic-gabbro composition somewhat enriched in iron, i.e. gabbro sample WG-14. After emplacement, this magma cooled and crystallized slowly so that the denser phases, olivine, ilmenite, titaniferous magnetite and aluminum spinel, settled under the influence of gravity. Cumulophyric aggregates of plagioclase much larger than the olivine, ilmenite and titaniferous magnetite also settled, but apparently only when denser mineral grains were included in the aggregates. Plagioclase grains by themselves appear to have floated because the cumulus plagioclase making up the framework of the gabbroic rocks is the same composition as that in the melatroctolite. Plagioclase of this composition (An_{59}) would, at 1200°C and pressures in the 0 to 2 kb range, have a density of about 2.63 gm/cc (Skinner, 1966). However, if a cumulophyric aggregate of these plagioclases included 5 percent olivine (Fo_{63}) by volume, a reasonable estimate based on thin section studies of these rocks, the density of the aggregate would be increased to 2.68 gm/cc under the same P-T conditions. Inclusion of a few grains of titaniferous magnetite would increase the density even further. Now if individual crystals of plagioclase An_{59} actually did float in the parent magma of the Melatroctolite-Gabbro Complex, the density of this magma would have to lie between 2.63 and 2.68 gm/cc. Using the data of Bottinga and Weill (1970), the density of a magma with the composition of sample WG-14 (19 wt% Al_2O_3) was calculated and found to be 2.66 gm/cc at 1250° C and 1 atmosphere pressure. This number would be changed by the addition of some small amount of water to the magma, and by the fact

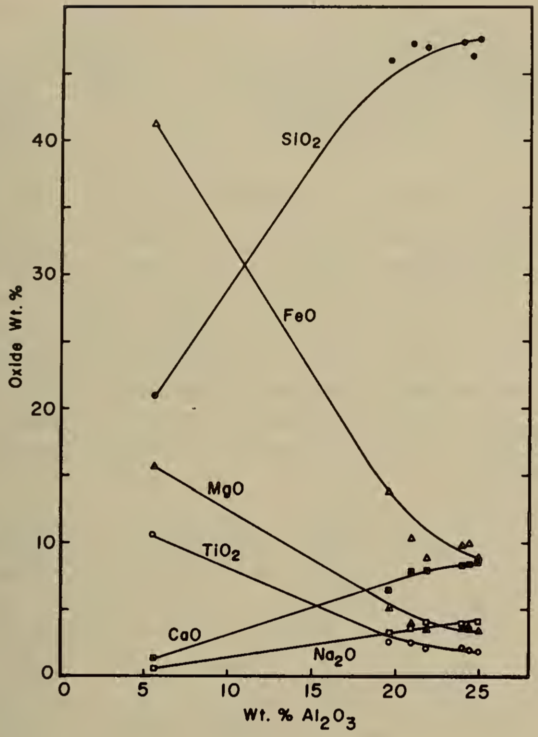


Figure 3: Variation diagram in which the major oxides are plotted against Al_2O_3 for the average melatroctolite and the six gabbro samples analyzed. Of the samples analyzed, WG-14, the assumed chill margin sample, has the lowest Al_2O_3 abundance.

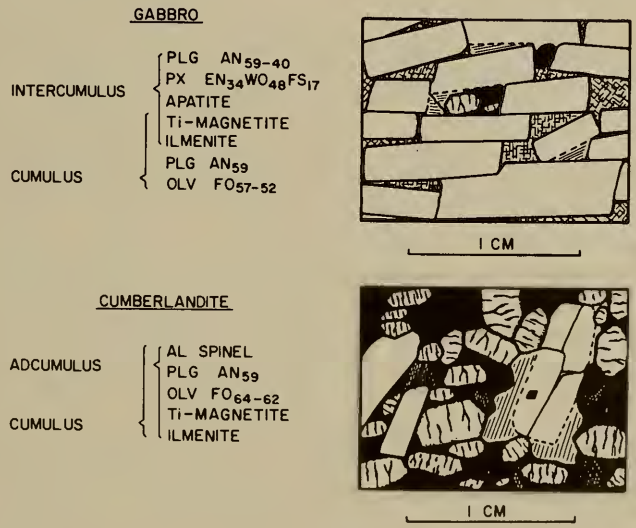


Figure 4: Summary of textures and mineral chemistries in the melatroctolite and anorthositic gabbro in the context of a comulus and adcumulus origin.

the magma was under some pressure, but these two effects would tend to compensate each other. It does appear that plagioclase could have floated while aggregates of plagioclase containing as little as 5 percent olivine by volume sank in a parent magma similar to the more mafic of the anorthositic gabbros.

The origin proposed for the melatroctolite is one of crystal growth in a magma accompanied by gravity induced settling of minerals and mineral aggregates more dense than plagioclase. The process of mineral accumulation apparently was sufficiently slow that the liquid interstitial to the cumulus minerals continuously re-equilibrated with the larger body of liquid above, and the intergranular areas were gradually filled with unzoned overgrowths of the cumulus minerals. The melatroctolite is thus a perfect example of an adcumulate igneous rock (Wager et al., 1960). Figure 4 summarizes the mineral chemistries and textures in the two rocks in terms of the cumulus-adcumulus origin.

The cumulus-adcumulus origin postulated above explains all of the unique mineralogical, textural and structural features in the melatroctolite and the anorthositic gabbro.
1) The foliation resulting from the planar orientation of the thin tabular plagioclase crystals and crystal aggregates indicates a cumulate origin for the rocks.
2) The complete lack of chemical zonation in the melatroctolite minerals and the subophitic texture of plagioclase with respect to olivine and opaques would be expected if crystal cumulation were slow, with the opportunity for large amounts of adcumulate overgrowth buffered by a relatively large magma reservoir above.
3) The tendency of olivine, titaniferous magnetite and ilmenite to develop an equilibrium texture consisting of planar grain boundaries and near 120° triple junctions is consistent with slow crystal growth and accumulation.
4) The inclusions of gabbro in the melatroctolite and the similarities in the cumulate mineralogy indicate the melatroctolite and the anorthositic gabbro were forming contemporaneously, presumably at the base and the top of the magma chamber respectively.
5) The absence of pyroxene in the melatroctolite, other than in gabbro inclusions, and the fact that it is only present interstitially in the gabbro indicates that Ca-pyroxene was not one of the early liquidus phases in the crystallization of the melatroctolite-gabbro parent magma. This interpretation means that the gabbro inclusions in the melatroctolite would not have been totally crystalline at the time of their inclusion.
6) The compositions of the large cumulus titaniferous magnetite and ilmenite crystals in both the melatroctolite and the anorthositic indicate that exchange of iron and titanium stopped at 950°C ± 100°C and at an f_{O_2} of $10^{-12.5 \pm 1.0}$. This appears a bit low to be an igneous crystallization temperature, but it is the temperature at which an iron titanium oxides first appear on the liquidus of a moderately primitive oceanic tholeiite (Helz, 1973; Dixon and Rutherford, 1980). In addition,

three hydrothermal experiments ($P_F = .67 P_{H_2O}$) have been done on the WG-14 Gabbro, and at 1000°C the products contain glass and less than 10% olivine and iron-titanium oxides. At 1060°C the sample was completely glass and at 900°C the sample had undergone very little melting. A few more experiments should be done, but the results to date support the cumulate model presented for the origin of these rocks.

PERALKALINE GRANITES

Regional Setting

Peralkaline granites exposed in northern Rhode Island lie near the southern end of a northeast trending zone of igneous activity which affected eastern New England during Upper Ordovician to (possibly) Lower Devonian time. Plutonic rocks similar to the Rhode Island peralkaline granites and probably emplaced during the same general period of magmatism include the Quincy, Cape Ann and Peabody Granites of eastern Massachusetts (Zartman and Marvin, 1971) and the Cadillac, Tunk Lake and related Granites in the Bar Harbor area, coastal Maine (Naylor and Sayer, 1976). Hermes et al. (1978) have also recovered peralkaline granites of Upper Ordovician age from bedrock outcrops in the Gulf of Maine. The origin of the peralkaline granites of New England is a question of fundamental importance. Further study of the granites should improve our understanding of the petrogenesis of these rocks and of peralkaline, silica-rich plutonic rocks generally.

Petrology and Mineralogy

The outcrops of peralkaline riebeckite granite in northern Rhode Island have been tentatively correlated with the Quincy Granite of eastern Massachusetts (Quinn, 1971). This correlation is primarily based on similarities in mineral composition and texture. The occurrence of equigranular granite with granite porphyry in both Quincy, Massachusetts and northeastern Rhode Island lends further support to this correlation (Quinn, 1971).

The equigranular variety of Rhode Island peralkaline granite appears as a light to medium gray, fine (near margins) to coarse grained, generally massive rock which has been introduced as small sills and irregular, partly concordant bodies. The granite is composed mainly of microperthite (40-70%), quartz (15-40%), and reibeckite plus aegirine (10-20%). Accessory minerals include purple fluorite, zircon, Fe-Ti oxides, aenigmatite, astrophyllite, and biotite. The amounts of the Fe-Mg phases (riebeckite, aegiritic pyroxene and Fe-Ti oxides) are quite variable, but the equigranular granite contains primarily amphibole and pyroxene with amphibole being somewhat more abundant.

The porphyritic variety of the Rhode Island peralkaline Granite appears compositionally similar to the equigranular variety based on petrographic work (chemical analyses have not yet been completed) and intrusive bodies containing both varieties have been noted by Quinn (1971). A contact between the equigranular and porphyritic granite types has not yet been observed by the authors. The relationship between the two granite types is important to understanding the origin of these two rock types, however; and more extensive field work must be done. The major differences between the equigranular and porphyritic peralkaline granites is the porphyritic texture in the latter, and the fact the riebeckitic amphibole is rare in the porphyry. However, the quartz and microperthitic feldspar phenocrysts in the prophyry are no larger than those in the equigranular granite, the porphyry just has a fine grained ground mass which comprises 30-70% of the rock. The most abundant ferro-magnesian minerals in the porphyry are the Fe-Ti oxides which occur in the matrix and as inclusions in the phenocrysts rims. The common amphibole is generally green in color rather than the distinctive deep blue of the Na-rich riebeckite.

Origin and Emplacement

Relatively little work has been done on the petrology and petrogenesis of the peralkaline Rhode Island granites and many questions remain unanswered at this time. Some of the major questions we hope to answer include the following:

1. What were the conditions for emplacement i.e., temperature, pressure, f_{O_2}, f_{H_2O} ?

2. How important was fluorine (f_{HF}) and what are its effects on the mineral assemblages produced from a peralkaline granite magma?

3. What is the relationship between the equigranular granite and the granite porphyry? Are they products of the same magma or two similar magmas? What is the reason for the porphyritic texture?

Although much more work is needed before we can answer all of these questions, some preliminary observations can be made. Emplacement of the granites in a liquid or partially liquid state is indicated by the presence of fine grained (1 mm or less) granite showing flow banding near the margins of some intrusions (e.g. Stop 2). Crystallization at relatively high temperatures is indicated by the hypersolvus, one feldspar nature of the granites. The only analysis of a homogenized alkali feldspar phenocryst completed (Ab_{68}), together with available data on the alkali feldspar solvus (Yund, 1975) indicate that the granitic magma must have crystallized at a temperature above 650 ° C. The fact that the alkali feldspar exsolution in both the equigranular and porphyritic granites is on a scale of less than .03 mm would also suggest a fairly rapid cooling rate, that is, emplacement at a relatively shallow level in the crust.

The riebeckitic amphibole in the peralkaline granites is also a potential source of petrogenetic information. The amphibole could have crystallized entirely in the subsolidus as suggested by Buma et al. (1971) in describing the Quincy Granite in Massachusetts, but two petrographic observations suggest that the riebeckite crystallized in the presence of a melt in the Rhode Island rocks. First, it is present as euhedral crystals making up part of the granitic mosaic in the fine grained margin sample (Stop 2). Second, riebeckite is present as small but abundant inclusions in the cores of some alkali feldspar crystals in the prophyritic granite. In at least one sample the riebeckite inclusions are replaced by Fe-Ti oxides in the rim of the phenocrysts. Experimental data (Ernst, 1962) indicates that riebeckite is stable as high as 650° C. This would appear to be subsolidus, but we have not yet considered the effect of fluorine, an important component in the magma judging by the fluorite present in the rock. By analogy with the work of Holloway and Ford (1975), fluorine should increase the stability of riebeckite, and it will tend to lower the solidus of the granite (Manning et al., 1980). Therefore it does seem possible that the riebeckite in these granites crystallized from a melt.

At this stage of the investigation, the most likely explanation for the textural differences between the equigranular and porphyritic granites is the volatile loss model. As proposed by Tuttle and Bowen (1958) and recently by Lyons and Krueger (1976), a rock like the equigranular peralkaline granite probably crystallized without loss of volatiles. According to this model, the porphyritic granite bodies would have partially crystallized under the same conditions and then suffered volatile loss. This loss of volatiles would quench the remaining melt to form the fine grained, generally anhydrous matrix. An origin such as this would explain the similarity in grain size between the granite and the phenocrysts in the porphyry, the amphibole inclusions in the phenocryst cores, and the Fe-Ti oxides in the matrix (and in some phenocryst rims), of the porphyry. It still remains to be determined whether this model can explain what appears to be significant chemical differences between different bodies of porphyry indicated by the relative abundance of quartz and microperthite phenocrysts.

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ROAD LOG

Mileage

0 Mileage starts at intersection of Interstate 295 and RI Route 122 in northern RI. Get off 295 at 122 North (to Cumberland, RI) and drive north on 122.

0.3 Almacs Shopping Center on left. Assemble in shopping center parking lot at 9:00 AM.

\- Drive North on Route 122

2.4 - Nate Whipple Highway goes off to Right

2.6 - Turn Right on West Wrentham Road

3.5 - Quincy-type peralkaline granite porphyry

3.7 - Quincy-type equigranular granite

4.6 - STOP 1. Melatroctolite-Anorthositic Gabbro Complex. Park on the left in the sandy area just past the power line. We will be walking down the power line and will be away from the cars for a couple of hours. Walk 50 yards down the power line then right along the ridge to the first outcrop.

STOP 1-a. In the Melatroctolite Quarry. The melatroctolite (Cumberlandite in literature) is composed of olivine (49%), titaniferous magnetite (32%), plagioclase (15% avg.) and smaller amounts of ilmenite (2%) and hercynitic spinel (2%). Unfortunately most of the exposed melatroctolite is the altered variety - the plagioclase is partially or completely converted to epidote and chlorite (in stages garnet has subsequently formed from these plagioclase alteration products.) Fresh melatroctolite occurs in a ledge along the southwest side of the quarry and is very abundant among the boulders south of the quarry (on the way to Stop 1-b).

The texture of the rock is that of tabular plagioclase aggregates (< 2 cm) in a finer-grained mosaic of olivine (1 mm - 1 cm) and titaniferous magnetite (<2 mm) as shown in Figure 3. The plagioclase tends to have a preferred orientation in much of the melatroctolite giving the rock a weak foliation which has been interpreted as an igneous lamination. In thin section the plagioclase looks to have some overgrowths, but the crystals are completely unzoned (An_{59}). The titaniferous magnetite, olivine and ilmenite often appears to meet with near perfect 120^{o} triple junctions, an equilibrium texture. They are also unzoned (Olv = Fo_{64}, $Ilm_{94}Hm_6$ and $Mt_{26}Olv_{63}Hc_{10}$) although the titaniferous magnetite has undergone subsolidus exsolution and oxidation. The chemistry of the coexisting titaniferous magnetite and ilmenite indicate a last equilibration temperature of 950°C ± 100 and a $Log_{10}\ f_{O_2}$ of -12.5. All of these textural and chemical data appear to be explained by invoking an extreme accumulate origin for the melatroctolite from a magma which was at essentially the same time crystallizing higher in the chamber to form the adjacent Anorthositic Gabbro. The only observation which cannot be easily explained is the different attitudes of the igneous lamination in the two rocks

STOP 1-b. Walk back out to the power line and southwest along it to the first anorthositic gabbro outcrop - Stop 1-b. Along the way are many nice boulders of unaltered melatroctolite. Some of these contain the best inclusions of anorthositic gabbro found in the melatroctolite.

The anorthositic gabbro at Stop 1-b has been affected by metamorphism and deformation more than in most other areas of the intrusion. The altered gabbro weathers grey-white due to the recrystallized nature of the plagioclase. The unaltered gabbro which can be seen here in several places is grey weathering and consists of cumulus plagioclase ($An_{59}Ab_{30}$) with minor olivine (Fo_{54}) and titaniferous magnetite and intercumulus plagioclase and Ca-rich pyroxene (Fig. 3). On a freshly broken surface the plagioclase (1 cm x 1 mm) tablets are black and oriented to give the rock a pronounced foliation (igneous lamination). The attitude of this lamination has been mapped throughout the area.

Sample WG-14 (Table 1) a somewhat finer-grained more equigranular (but partially altered) sample of the gabbro was taken about 100 yards to the south of Stop 1-b. The WG-14 outcrop is only 50' from the Esmond granite contact, and was thought to be the best candidate for a chilled margin sample. A much better chilled margin locality has now been found (Stop 1-d).

STOP 1-c. Continue southwest along the power line (800') to the intersecting NW-SE trail and walk 1000' northwest along the trail.

Stop 1-c is an anorthositic gabbro outcrop 100' west of the trail. This outcrop shows the best example of rhythmic layering found in the gabbro. The layering which strike N 40° W and dips 45° NE is parallel to the igneous laminations in the rock. Apparently with 19% Al_2O_3, the magma became too viscous to allow significant crystal segregation.

STOP 1-d. Continue NW on the trail, crossing a NE-SW trail (about 1800' from the power line) and Stop 1-d is on the hill to the right just past this intersection. Normal anorthositic gabbro occurs on the hill, but as you go further north, down the hill toward the stream, the rock becomes fine-grained (1 mm) and very massive. Large (up to 2 cm) phenocrysts of plagioclase are scattered through the matrix and are the only phenocrysts identified at this time. Work is still in progress on this particular rock-type however because it looks like an excellent chilled margin sample. The Sneech Pond schist with sills and dikes of Esmond granite occurs just across the stream (50').

Return to the cars along the same route followed on the way in.

4.8 - Continue driving north along West Wrentham Road

- Sneech Pond Schist with dikes and sills of Esmond on Right

5.3 - Turn Right on Route 114

6.1 - Sneech Pond Schist over most of this hill, but Hunting Hill Greenstone lithology does occur on the right just past the power line.

6.6 - Stop 2 - We will come back to it after lunch. Mileage stops here, we'll pick it up after lunch.

Lunch stop is in Diamond Hill State Park. Continue past Stop 2, turn right on 114 (South) for 1/2 mile and left into the State Park. There is a picnic area 150 yards in bearing left (North).

- Return to Stop 2 after lunch. Park on road which goes to the North at the bottom of the Hill.

STOP 2. QUINCY-TYPE PER-ALKALINE GRANITE

The outcrop at the bottom of the hill is at the northern edge of the large body of equigranular per-alkaline granite in this area (Fig. 2). At the east and west edges of the road cut outcrop the granite is fine to medium grained (1 mm). The granite in the center of the outcrop is coarse-grained (1 cm) with numerous quartz pads and lenses containing coarse fluorite, amphibole, biotite, and Fe-Ti oxides. The central part of the outcrop is cut by an 8 foot thick, vertically dipping slightly altered diabase dike which has not been noticeably deformed and is therefore probably Triassic (Quinn, 1971). The finer grained granites have a moderately well developed foliation (120°/40°N) and a mineral lineation plunging 40° to the NE in the plane of the foliation. The finer-grained rocks also occur close to the margins of the granite, the Porphyritic Grant-Mills Granodiorite on the west and Sneech Pond Schist to the North and East. As a consequence, the foliation and lineation are interpreted as induced by flow during emplacement of the granite, although there certainly has been some post-emplacement deformation. The textures and mineralogy of the rocks as seen in this section are consistent with this interpretation.

The granites are composed of microperthitic alkali feldspar (50%) quartz (30-35%) and variable amounts of aegiritic pyroxene, riebeckite and Fe-Ti oxides totalling from 10-20%. Important minor and trace minerals include fluorite, aenigmatite, sphene and calcite. In thin section the coarse granite appears to have suffered more from deformation in that the large quartz grains which remain show prominent underlatory extinction. The subgrain boundaries are elongate and pseudo parallel giving the rock a weak foliation. Some of what once were large quartz grains appears to have recrystallized to a finer-grained (1-2 mm) mosaic. The ferromagnesian minerals in this coarse-grained granite are predominantly pyroxene and Fe-Ti oxides; minor amounts of riebeckite occur in the matrix and in the feldspar grains. In contrast, riebeckite and aegiritic pyroxene occur in approximately equal amounts and Fe-Ti oxides are a minor phase in the finer-grained granites. The modes of the fine and coarse-grained granites are essentially identical in terms of the quartz (40%) and microperthitic alkali feldspar (45%). These textures and modal variations are consistent with an origin for these per-alkaline granites involving volatile loss during the crystallization of some parts of the intrusion (i.e. see Lyons and Krueger, 1976). However, more work on the rocks is obviously required before this or any emplacement hypothesis can be accepted.

\- Leave STOP 2 going East on 114.

6.8 - Intersection 114 & 122. Turn South on 114

8.6 - Junction of 114 and Nate Whipple Highway. Turn right on Nate Whipple Highway (at traffic light)

9.5 - STOP 3 (optional) PER-ALKALINE GRANITE PORPHYRY

Park on Staples Road which goes off to the Right.

The per-alkaline granite porphyry exposed here is composed of about 25% by volume phenocrysts (<1 cm) of quartz and microperthitic feldspar in a fine (<1 mm) groundmass of microperthitic feldspar, quartz and ferro-magnesian minerals. As a whole the rocks consists of 44% quartz, 35% microperthitic feldspar and 15% ferromagnesian minerals, predominantly olive-green amphibole and Fe-Ti oxides with minor biotite. Fluorite is prominent among the accessory minerals. Green amphibole is present in the cores of feldspar phenocrysts and is replaced by small euhedral crystals of titaniferous magnetite in the phenocryst rims. Is this rock similar to the more equigranular type per-alkaline granite such as seen at Stop 2 and can the differences be explained simply by invoking different emplacement conditions? This is one of the main questions we have been trying to answer, this and the question of the emplacement conditions.

Aside from the differences in the ferromagnesian minerals in the two types of granite, the only other major difference is textural. The quartz and alkali feldspar phenocrysts in the porphyry are almost all frayed looking and somewhat augen shaped. Trains of ferromagnesian minerals in the matrix give the rock a prominent foliation 120°/30°N). The long axes of the augen are parallel to this foliation.

Continue West on Nate Whipple Highway

10.1 - Sneech Pond Schist on the Right

10.7 - Turn Right on road just past the Cumberland Medical Center. Sneech Pond is just to the North. Parking is limited at this stop - some cars may have to use the Medical Center lot.

10.9 - Park on Right in power line right of way.

\- STOP 4 (optional) PER-ALKALINE GRANITE PORPHYRY

Walk North along the power line to the outcrop of granite porphyry at the water's edge (500 yds.). On the way you will pass several outcrops of Sneech Pond Schist.

The granite porphyry at this stop is very similar to that at STOP 3 except the ratio of phenocrysts to matrix is higher in this outcrop (10% vs 25%) and there is almost no foliation visible in thin sections of this (STOP 4) rock. The total abundance of ferromagnesian minerals is somewhat lower in this rock, but once again the main minerals are Fe-Ti oxide and green amphibole. There is a trace of riebeckite in this sample. The rock at STOP 4 appears texturally close to the equigranular per-alkaline granite of STOP 2, but the volatile rich ferromagnesian minerals are not present.

The foliation that can be seen in the outcrop at STOP 4 is not parallel to the trend of this sill-like body (NW-SE; see Fig. 1). However, samples were taken from what is considered to be the same sill-like body across the pond to the northwest, and one sample taken a few feet from the Sneech Pond Schist contact appears to have good flow banding parallel to the sill boundaries.

This particular sample contains approximately 15% by volume of euhedral, sharp cornered phenocrysts (microperthite and quartz) in an extremely well foliated matrix where the main ferromagnesian mineral is an Fe-Ti oxide.

The nearby contact of the granite porphyry with the Sneech Pond Schist is indicated by inclusions of dark schist at the northeast edge of this (STOP 4) outcrop.

Return to cars

- Drive out to Nate Whipple Highway and turn Right
- Intersection of Nate Whipple Highway with Route 122. Turn Left and follow to intersection with Interstate 295.

CONTACT RELATIONSHIPS OF THE LATE PALEOZOIC NARRAGANSETT PIER GRANITE AND COUNTRY ROCK

O. Don Hermes[1], Patrick J. Barosh[2] and Paul V. Smith[2]

INTRODUCTION

The Narragansett Pier Granite (NPG) is a post-tectonic Permian pluton that exhibits complex intrusive relationships into country rocks of diverse ages, lithologies, and structures; these include the Hope Valley Alaskite (HVA), Ten Rod Granite (TRG), Blackstone Series (Plainfield formation of CT) and associated gneisses and amphibolites, and Pennsylvanian rocks of the Rhode Island Formation. The pluton exhibits many of the characteristics of an S-type granite (Chappell and White, 1974), and cross-cuts the structural trends of rocks within the Avalon Zone. The pluton, which is batholithic in size (∿100 mi^2) (Fig. 1), extends eastward from southeastern Connecticut across southern Rhode Island to the eastern boundary of Narragansett Bay. The pluton may extend southward beyond the southern Rhode Island coastline, but recent off-shore geophysical measurements do not provide definitive evidence (McMaster et al., 1980).

The NPG is a remarkably homogeneous pluton, in terms of modal mineralogy and chemistry. However, some textural and color variations exist which have permitted three distinct and mappable facies to be recognized (Fig. 1): 1) pink, medium- to coarse-grained equigranular granite, 2) pink, coarse-grained porphyritic granite, and 3) a white, medium- to coarse-grained equigranular-porphyritic facies (Kocis, 1981; Kern, 1979). The batholith is cut by simple to complex veins of aplite, pegmatite, and quartz; in addition, dikes of Westerly Granite (generally thought to be late-stage, but co-magmatic) and lamprophyric dikes that contain mantle-derived lherzolite nodules and megacrysts, locally cut the granite and the older country rock.

Dikes of NPG and Westerly Granite (WG) occur to the west in southern Connecticut (Liese, 1979), and recently it has been demonstrated that the NPG extends well to the north of the general contact mapped by Moore (1959). Emplacement of dikes of the NPG into country rock north of the general contact is thought to have been controlled in part by earlier shear zones, that may have been reactivated following granite emplacement (Smith and Barosh, 1980). Many xenoliths and pendants are present in the NPG and the borders of the pluton generally have wide zones mixed with country rock. A remarkable alignment of the structural fabric between the blocks of country rock indicates a relatively passive manner of emplacement of the NPG.

The purpose of this trip is to investigate some of the diverse contact relationships exhibited by the NPG, and to see representative outcrops of most facies varieties of granite as well as adjacent country rocks.

[1] Department of Geology, University of Rhode Island

[2] Department of Geology and Geophysics, Weston Observatory, Boston College

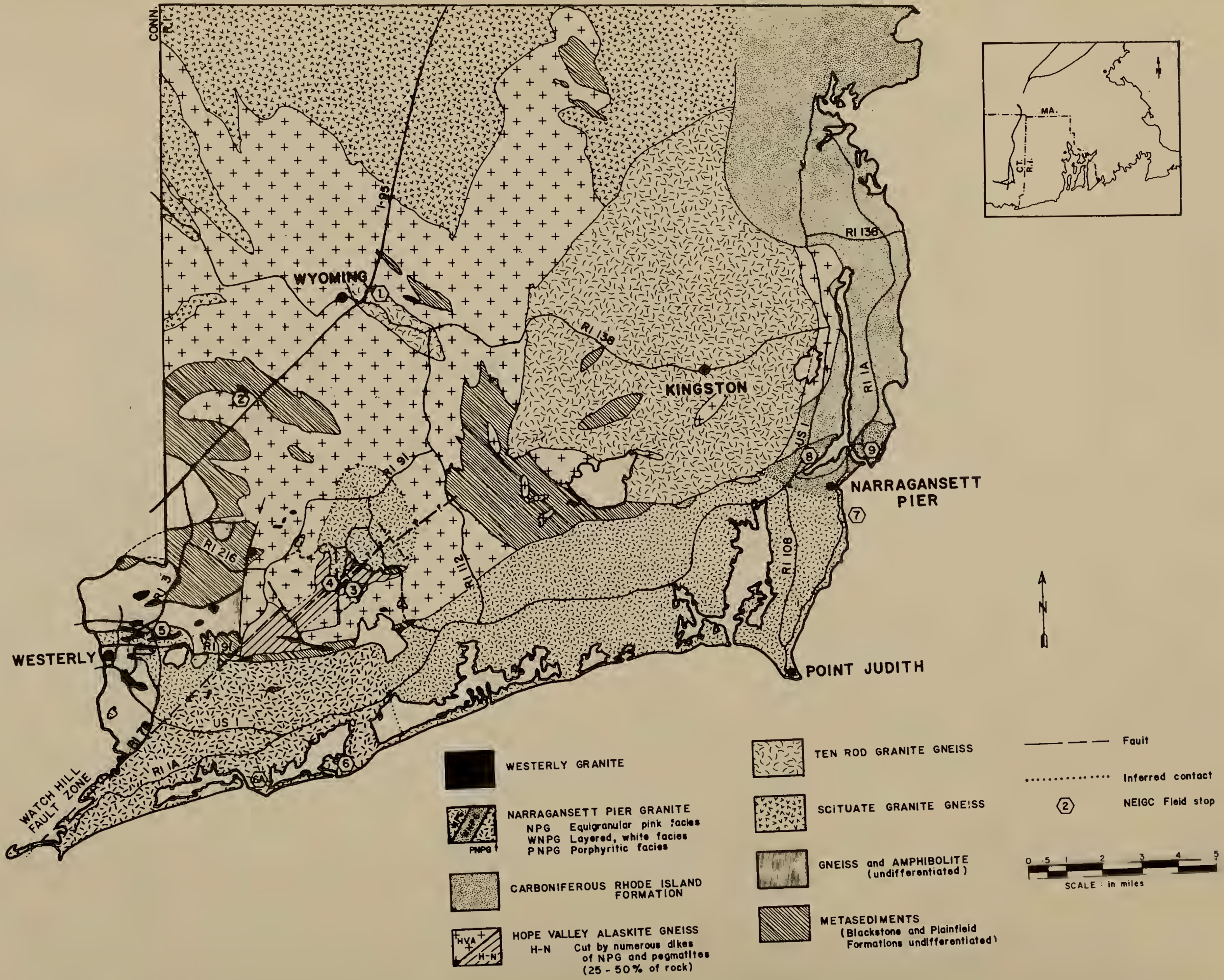

FIGURE 1. Generalized geologic map of southern Rhode Island west of Narragansett Bay, showing field trip stops.

REGIONAL SETTING

Rhode Island lies to the southeast of a major thrust belt that includes the Clinton-Newbury, Bloody Bluff and Lake Char faults (Fig. 1 inset). Rock types and structures in Rhode Island are distinctly different from those in both the thrust belt and the areas to the west of it (Barosh et al., 1977). This difference, combined with the metamorphic history and paleontologic investigations of fossilized fauna types present to the southeast of this fault system has led many geologists to correlate this area with the Avalon Zone of Newfoundland that also lies east of a major structural break. The Avalon Zone may have been a late Precambrian-early Paleozoic microcontinent or island arc that acted as a stable platform to the east of the Acadian orogenic belt (Rast et al., 1976), and was welded onto the North American plate perhaps as late as the Devonian (Gaudette, 1981; Zartman and Naylor, in press).

Eugeosynclinal sedimentary and volcanic rocks of the Blackstone Series intruded by rocks of the Sterling Group (Scituate Granite Gneiss, HVA and TRG) constitute much of the Avalon basement in Rhode Island. These rocks were intensively deformed as they were intruded, probably during the Late Precambrian, into folds that broke as deformation continued. This structure is especially complex in southwestern Rhode Island (Fig. 2) and locally controlled the emplacement of the NPG. To the northeast in Massachusetts and offshore in the Gulf of Maine, an extensive late Ordovician to Early Devonian period of alkaline-peralkaline magmatism is recognized within the Avalon terrain (Zartman and Marvin, 1971; Zartman, 1977; Hermes et al., 1978). Recent geochemical work and zircon geochronology demonstrates that alkalic plutons of Devonian age are rather widespread in Rhode Island as well (Hermes and Zartman, unpublished data; elsewhere in this volume), but major calc-alkaline plutonic events of mid-Paleozoic age have not been recognized, nor is there convincing evidence of either Taconic or Acadian deformation and metamorphism.

Dikes of lamprophyre locally cut the granite, and diabase dikes of Mesozoic age cut the adjacent country rock, but have not been observed to intrude the rocks of the NPG pluton.

AGE RELATIONSHIPS

Present data confirm that the NPG is an Alleghenian granite, probably intruded shortly after (and perhaps as a result of) the peak deformation and metamorphism of the Pennsylvanian rocks of the Narragansett Basin and the older adjacent crystalline rocks. Previous lead-alpha determinations on zircon (208-275 m.y.) and K/Ar measurements on biotite (230-260 m.y.) may be subject to errors or to partial resetting during the "Permian disturbance" (Zartman et al, 1970). Recent U/Pb ages on monazite from two samples (a pink and white facies sample, respectively) collected at Narragansett yielded ages of 276 and 277 m.y. (Kocis et al., 1977, 1978; Kocis, 1979). These ages are compatible with the recent find of Stephanian B plant fossils recovered from a carbonaceous-rich layer in a xenolith enclosed in granite of the white facies (Brown et al, 1978) (Stop 9 of this trip). Zircons from both the NPG and WG collected in the Westerly area presently are being dated by one of us (ODH), and these data should be available for the NEIGC trip.

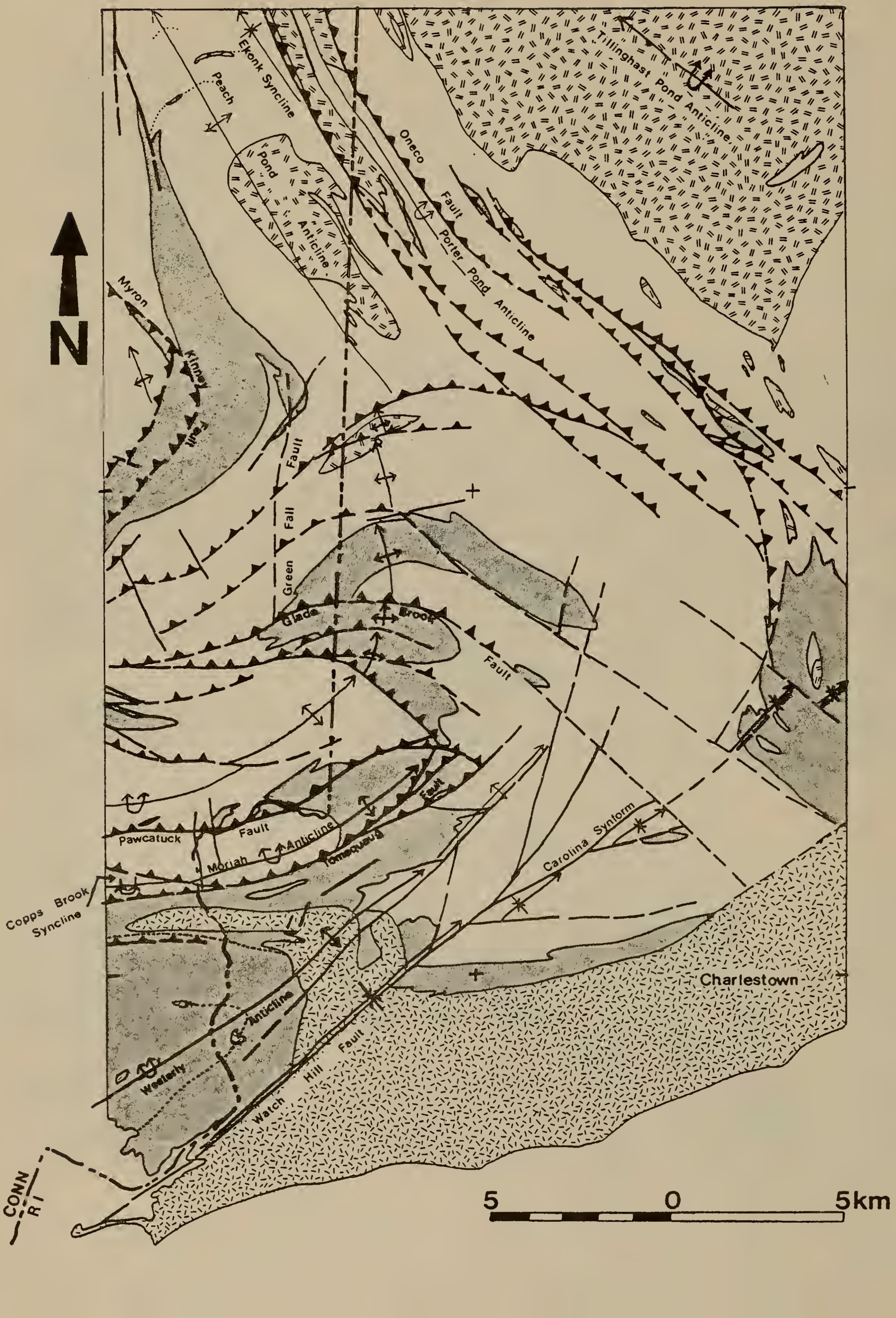
Ekonk Syncline
Peach Pond Anticline
Tillinghast Pond Anticline
Oneco Fault
Porter Pond Anticline
Myron Kinney Fault
Green Fall Fault
Glade Brook Fault
Pawcatuck Fault
Moriah Anticline
Tomaquaug Fault
Copps Brook Syncline
Carolina Synform
Westerly Anticline
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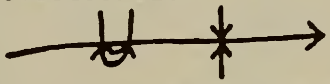
Figure 2: Bedrock geologic map of southwestern Rhode Island and southeastern Connecticut.

Explanation for bedrock geologic map of southwest Rhode Island and Southeast Connecticut.

▨	**Narragansett Pier Granite.**
▨	**Scituate Granite Gneiss.**
□	**Hope Valley Alaskite Gneiss and other granitic gneisses.**
▩	**Metasedimentary and Metavolcanic rocks**

Fault, dashed where approximately located, teeth on upper plate of thrust fault.

Anticline, axial trace showing plunge, barbs show dip where overturned.



Syncline, axial trace showing plunge, barbs show dip where overturned.

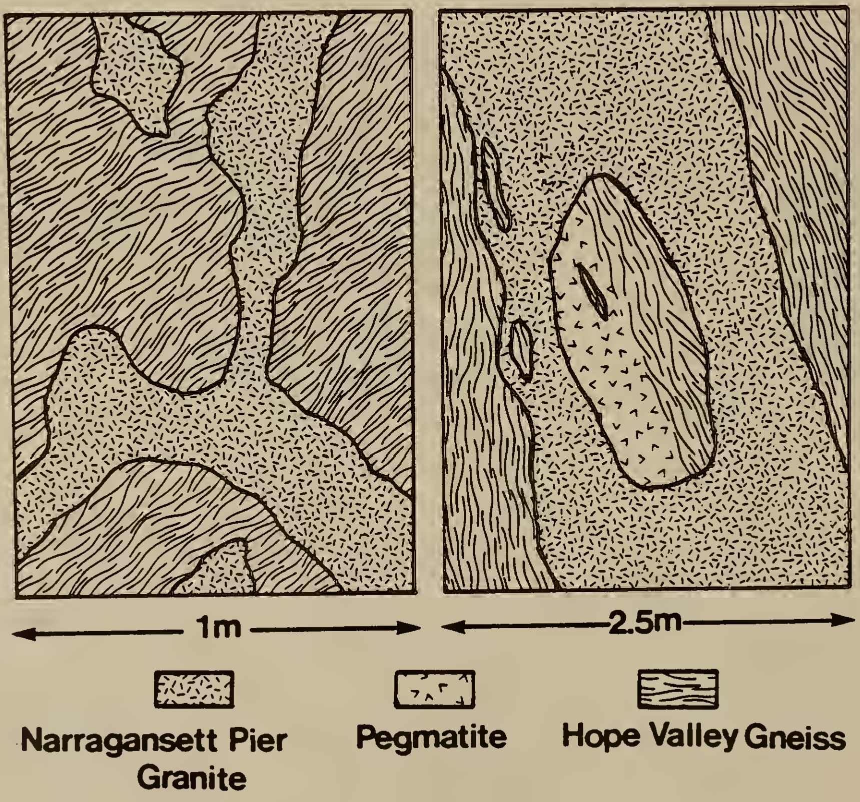
Contact, dashed where approximately located.

Inter-unit contact, for structural control.

The Permian age of the NPG makes it the youngest pluton thus far recognized in Southeastern New England. It is roughly contemporaneous with the Milford Granite of New Hampshire (Aleinikoff et al, 1979), and with the group of granitic plutons in the SE Appalachians dated at 265-325 m.y. (Fullagar and Butler, 1979).

STRUCTURE AND FIELD RELATIONSHIPS

Contacts between different facies of the NPG are nowhere exposed, and it is unclear whether they are gradational, intrusive or faulted. On the other hand, contacts with country rock are exposed in a number of places; in nearly all cases they exhibit a complex lit-par-lit relationship, generally concordant with the foliation and/or bedding of the intruded rock. Such is the case at Cormorant Point (Stop 9 in the NE part of the pluton), and in the Woody Hill and Charlestown areas. In many places cross-cutting dikes connect the lit-par-lit sills to form a patchwork of enclosed xenoliths (Figs. 3 and 4). The simplest exposed contact is in Westerly (Stop 5) where the NPG truncates the foliation of intruded amphibolite at a shallow angle, but even here, concordant veins of granite, aplite, and pegmatite cut the amphibolite a few tens of meters to the north.



FIGURES 3 and 4. Geologic sketches of typical intrusive relationships of Narragansett Pier Granite to country rock at Stop 2. Figure 3 shows irregular cross-cutting relationships; Figure 4 shows sill with enclosed xenoliths.

Drill core from the once proposed Nuclear Power Plant site at Charlestown, R. I., verify the complex interlayering of rock types within a few km. of the northern contact. The thickness of rock types and their relative positions vary abruptly over short distances (Fig. 5). These changes are interpreted to represent stoped blocks and roof pendants of country rock within the NPG (New England Power Co., 1975). Based on other exposed outcrops it seems likely that this zone itself is representative of the complex lit-par-lit style of intrusion that is characteristic of the contact zone. These relationships make it difficult to pinpoint the exact contact of the pluton, and necessitate invoking the use of the term "contact zone."

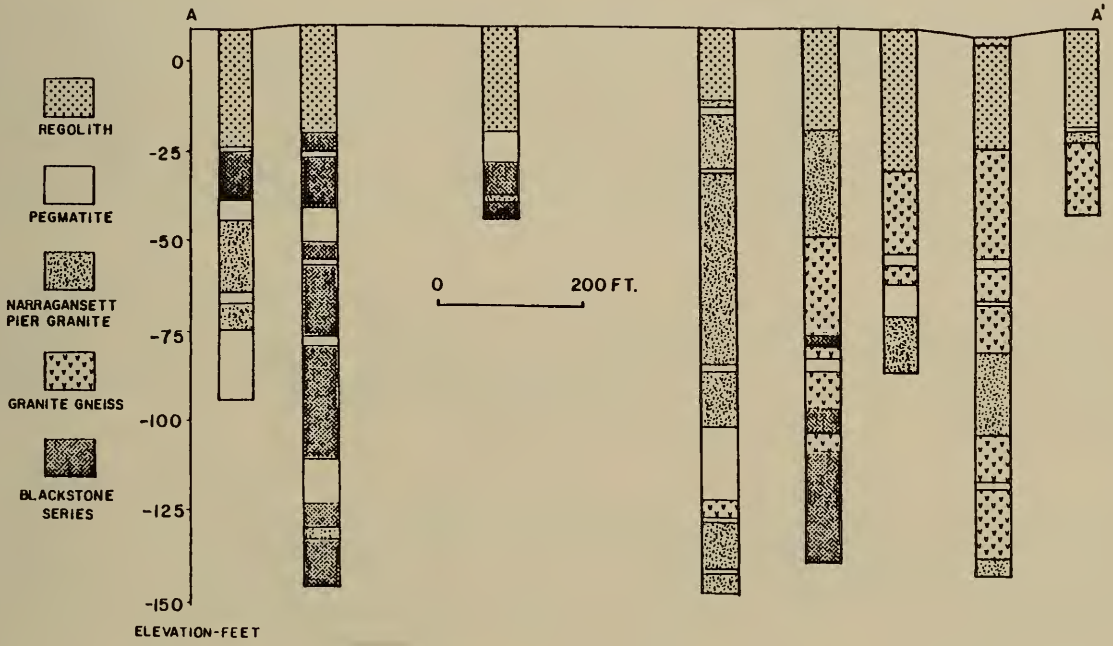


FIGURE 5. Representative core logs from contact zone of NPG (Charlestown, R. I.). The highly variable lithologies from hole to hole are similar to most exposed contact zones, and appear to represent the lit-par-lit nature of the intrusion as exposed elsewhere at the surface (from Preliminary Safety Analysis Report).

Xenoliths in the granite are common near the contact zone and become less prominent southward within the main pluton. Xenolith type correlates with the adjacent country rock, and in no cases have "restite-type" xenoliths been observed. For example, xenoliths at Westerly are exclusively varieties of amphibolite and biotite schist that contain mineral assemblages and modal proportions quite similar to the adjacent country rock (Kern, 1979). A short distance to the east, HVA forms most of the xenoliths as well as the country rock. The long dimensions of xenoliths are parallel to foliation, and moreover, the foliations exhibit similar orientations to foliations in the country rock. On a local scale, both Kern (1979) and Smith and Barosh (1981) have demonstrated that foliation in xenoliths wraps around, following the contact and the foliation in the country rock NE of Westerly. Xenoliths in the white granite facies near Narragansett are schists, sandstones, and conglomerates (some carbonaceous) identical to rocks of the intruded Pennsylvanian Rhode Island Formation (Kocis, 1981), and similarly exhibit foliation conformable to that in the country rock.

This consistent orientation of xenoliths and their structures testifies to the rather passive nature of the intrusion, in which only a few blocks were stoped and rotated. The country rock was pried apart along bedding and foliation planes to permit the lit-par-lit emplacement as a result of this gentle mode of emplacement, and the resultant screens of included rock represent a crude ghost stratigraphy that locally reveals the pre-NPG structure.

Although most of the NPG is massive, distinct flow foliation and/or layering is locally prominent. This can be observed in some of the quarries at Westerly, along Quonochontaug Beach, and at Watergate Cove in Narragansett. In these cases the layering is caused by concentration of biotite which exhibits crude cross-bedding and cut and fill structures. A special kind of textural layering is exhibited within the contact zone at Cormorant Point; here the structure is dominated by aligned xenoliths that generally are concordantly enclosed in alternating textural layers of aplite, pegmatite, and fine- to medium-grained granite that is low in mafic content.

The NPG is cut by gently south-dipping, west-trending dikes of Westerly Granite, especially in the western third of the pluton. The Westerly Granite generally is considered to be a late-stage, comagmatic facies of the NPG. Dikes of WG also cut the country rocks to the north of the pluton, and have been reported westward well into Connecticut (Liese, 1979).

In addition to the large dikes of WG, the NPG is cut by smaller veins of aplite, pegmatite, and quartz. Maczuga (1977) was able to demonstrate that aplites and pegmatites in the Narragansett area form three relative age groups: 1) oldest, NNW-strike with steep dips to the E or W, 2) intermediate, W-strike and steep dips N or S, and 3) youngest, NW-strike, with moderate to high dips to the SW or NE (Fig. 6). In the Quonochontaug and Westerly areas, the largest concentrations of veins of aplite and pegmatite strike W and have shallow dips to the S (Fig. 7); age relationships are not so apparent as at Narragansett, but suggest that these are the youngest veins. A second smaller maximum of veins with N to NW-strike exists.

Orientations of fractures in the Westerly area are mainly NE-striking with NW or SE dips, and less prominent NW- to N-striking fractures with steep dips. A fracture zone cuts the NPG along the extension of the Watch Hill fault zone and appears to be a reactivation of it (Stop 4). This fracture zone is broken by both N and NW offsets (Smith and Barosh, 1980) (Fig. 1). The NE-trending fractures with NW dips are also the most prominent at Narragansett, but N- and W-striking groups are present as well.

PETROGRAPHY AND GEOCHEMISTRY

All granite facies are structurally massive and non-foliated, except for local areas where flow foliation has developed.

FIGURE 6. Lower hemisphere plot of (A) pegmatites/aplites and (B) fractures from NPG outcrops along the eastern shore of Narragansett Pier (data from Maczuga, 1977).

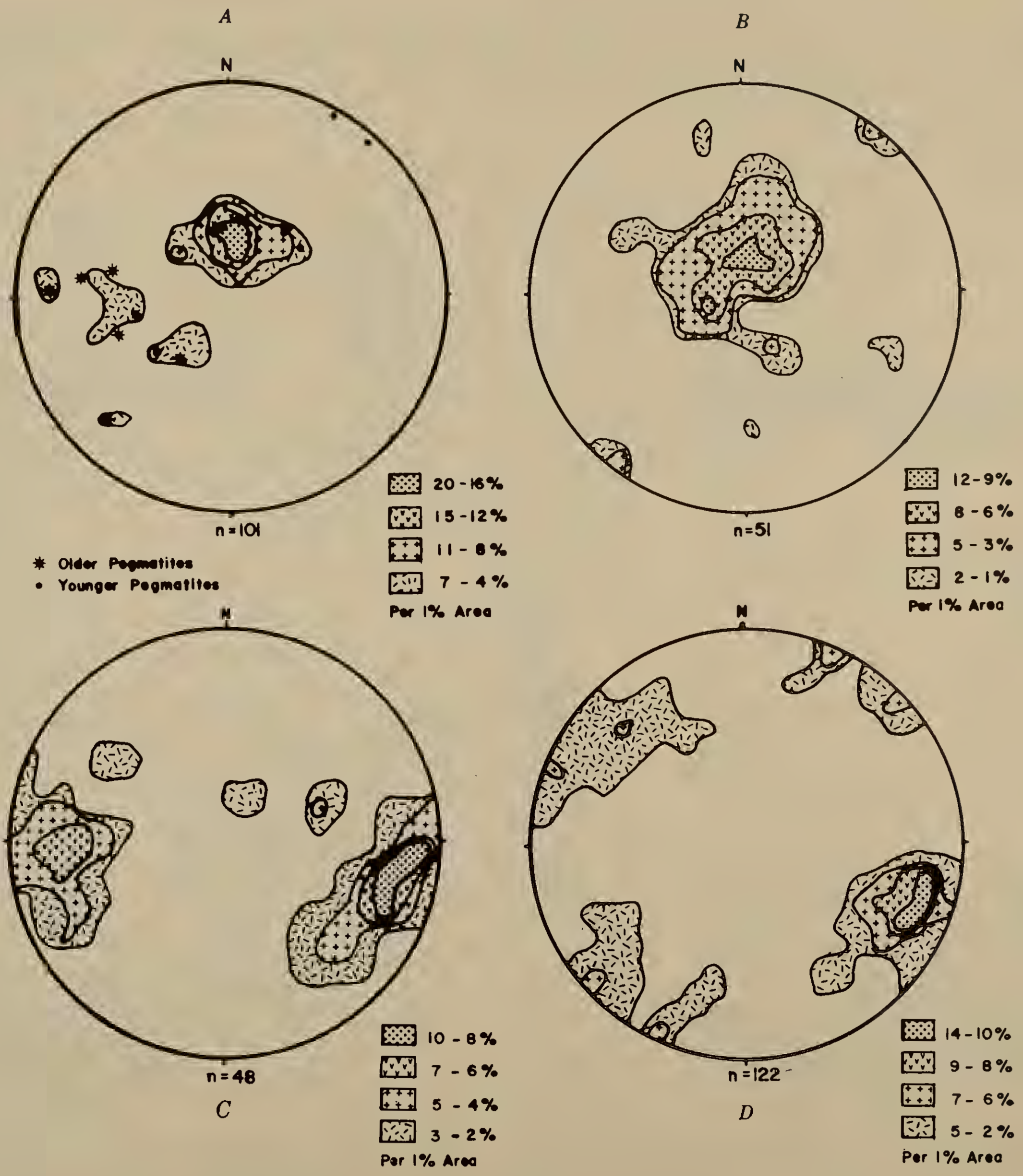


Figure 7: A, B. Lower hemisphere plot of pegmatites and aplites from the Quonochontaug/Weekapaug and Westerly areas, respectively. C and D illustrate fractures from these two respective areas (data from Kern, 1979).

The pink granite facies contains perthitic microcline, plagioclase, quartz, and biotite with accessory muscovite, magnetite, ilmenite, apatite, monazite, sphene, zircon, allanite, pyrite and chlorite. The pink color is due to oxidized iron along grain boundaries and fractures and included iron within feldspars. Grain size ranges from fine-grained to more commonly medium-grained (1-3 mm), but locally is coarser. The porphyritic facies generally is similar except that it contains phenocrysts of euhedral-subhedral feldspars up to 3 cm in a medium-grained groundmass.

The white granite contains the same major minerals as the pink variety, but contains common garnet as an accessory, and virtually no opaque minerals. In general the muscovite/biotite ratio is greater in the white granite (except where certain flow foliation is prominent) and muscovite commonly is euhedral and clearly primary.

Rocks of the NPG pluton fall mainly in the granite field, with a few from the eastern end of the pluton in Narragansett just crossing into the granodiorite and quartz monzonite fields (Fig. 8). Rocks of the porphyritic facies can not be distinguished from the equigranular pink facies on the basis of modal mineralogy. The white facies exhibits considerable modal variability and tends to be richer in quartz and generally lower in mafics (Fig. 8), except for varieties rich in garnet or samples that exhibit flow foliation and relatively high biotite contents. The pink facies as well as rocks of the white facies from Narragansett exhibit more scatter and appear to have a higher plagioclase/alkali feldspar ratio compared to the tight cluster of points for rocks from the west end of the pluton near Westerly.

Representative chemical analysis of rocks from most trip stops are shown in Table 1. The rocks are all peraluminous and contain 1-3% corundum in the norm. The overall range of chemistry exhibited is quite small and no significant difference between the equigranular and porphyritic pink varieties is apparent. The white granite at Thule Cove (Cormorant Point) is lower in CaO, MgO, TiO_2, and total Fe, and has a high Fe^{+2}/Fe^{+3} ratio compared to pink granite. Other white granite samples (not shown in Table 1) are intermediate in composition, and at Watergate Cove, where prominent flow layering is exhibited, the rock is indistinguishable modally and chemically from the pink facies eventhough it maintains its white color.

ACKNOWLEDGEMENTS

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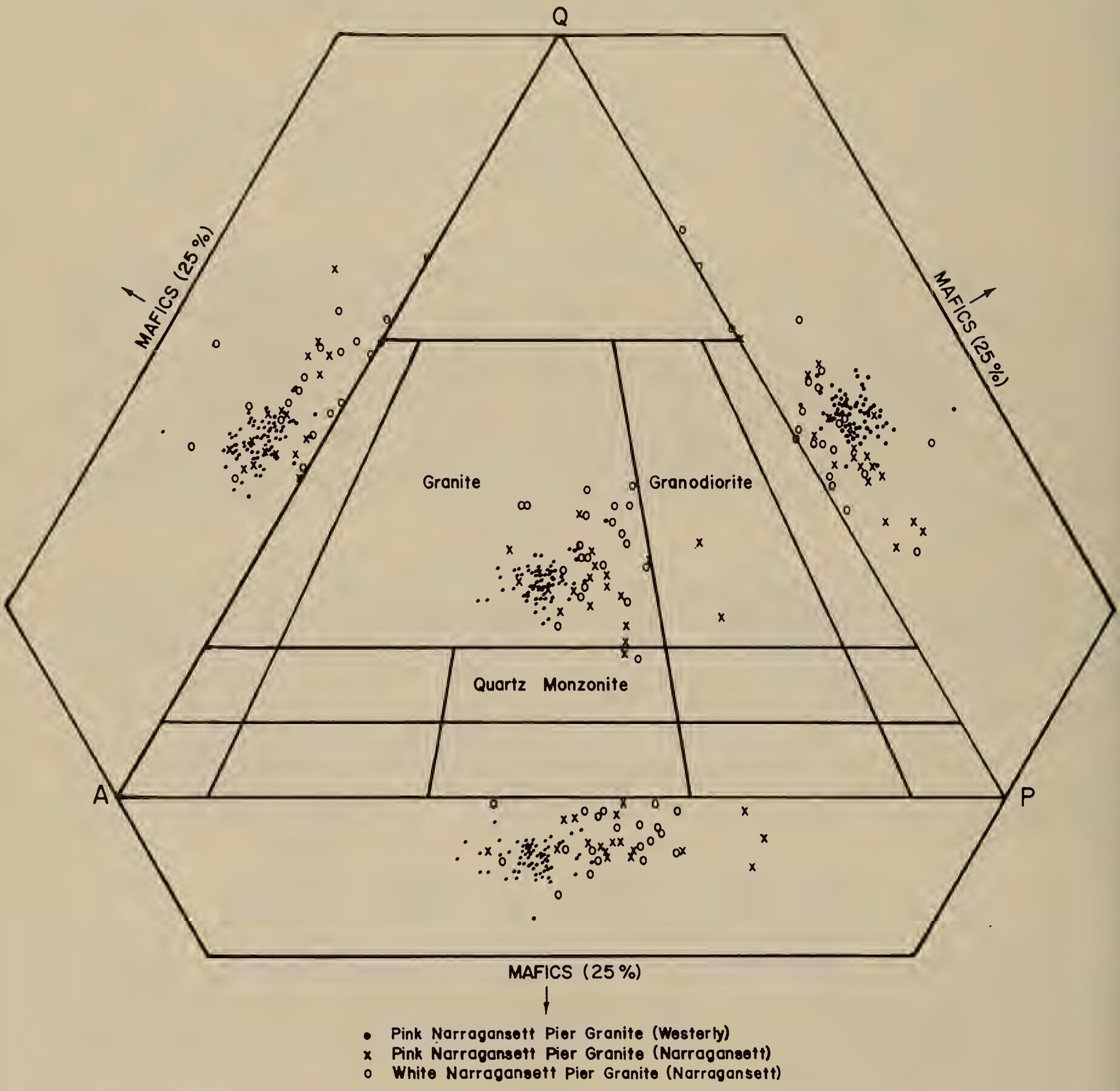

FIGURE 8. Plot of modal data for NPG (data from Kern, 1979; Kocis, 1981).

TABLE 1: Chemical compositions and CIPW norms of selected rocks of the Narragansett Pier pluton.

	1	2	3	4	5
SiO_2	71.96	70.45	70.59	74.30	74.89
Al_2O_3	14.26	14.09	15.76	15.18	14.71
Fe_2O_3	.86	.79	1.13	.39	.01
FeO	1.29	.96	.69	.26	.21
MgO	.49	.34	.42	.18	.07
CaO	1.58	1.18	1.14	1.05	.77
Na_2O	3.37	3.55	4.08	3.27	3.75
K_2O	5.06	5.13	4.99	4.35	4.88
H_2O	.17	.39	.91	1.34	.78
TiO_2	.45	.24	.29	.11	.08
P_2O_5	.10	.06	.05	.03	.03
MnO	.03	.02	.03	.01	.01
Total	99.54	97.36	100.09	101.15	100.21
Q	28.79	27.59	26.28	33.22	32.56
C	.61	.71	2.10	2.50	1.94
OR	29.98	31.14	28.44	29.36	28.75
AB	28.59	30.85	34.43	27.38	31.65
AN	7.20	5.61	5.05	4.96	3.59
EN	1.22	.87	.89	.44	.17
FS	.97	.77	.35	.08	.33
MT	1.25	1.18	.77	.43	.01
HM			.44	.09	
IL	.86	.47	.49	.21	.13
AP	.24	.15	.07	.07	.08

[1] Sample S78-1, pink, equigranular granite (Stop 5) Westerly (Kern, 1979).

[2] Sample NBF-1, pink, porphyritic granite (Stop 6) Quonochontaug area (Kern, 1979).

[3] Sample HA, pink, equigranular granite (Stop 7, average of 3 samples), Hazard Avenue, Narragansett (Kocis, 1981).

[4] Sample NA, white, equigranular granite (Stop 8, average of 3 samples), Narragansett Avenue, Narragansett (Kocis, 1981).

[5] Sample TH, white, equigranular granite (Stop 9, average of 3 samples), Thule Cove, Narragansett (Kocis, 1981).

ROAD LOG AND STOP DESCRIPTION

Miles

cum.	int.	
		Log starts at intersection of road to Keaney parking lot (University of Rhode Island athletic complex) and RI 138, Kingston, Rhode Island. Travel west on RI 138
10.1	10.1	Take entrance ramp to I-95 N.
11.0	.9	Road cuts on both sides of highway. Stop 1: INDICATIONS OF THE NORTHERN EXTENT OF THE NPG AND CHARACTERISTICS OF THE HOPE VALLEY ALASKITE (HVA) AND BLACKSTONE SERIES (Fig. 9).

The HVA intrudes metasedimentary rocks and is cross-cut by non-foliated pegmatite dikes of the type associated with the NPG. The HVA is characteristically light pinkish gray, medium- to coarse-grained, and foliated, with quartz rodding that appears as strong foliation in one direction and weak foliation in a perpendicular direction. The HVA occurs here as several sill-like bodies with sharp to broadly gradational boundaries with the Blackstone and contains xenoliths at various stages of digestion. The HVA is fine-grained along a few contacts that, therefore, appear slightly chilled. The metasedimentary rocks consist of several slightly different layers of medium- to dark-gray, fine- to coarse-grained biotite-hornblende gneiss, that locally is thinly layered and may be volcaniclastic. Intrusive relationships of the HVA exhibited here and at nearby outcrops discount the suggestion by Day and others (1980a,b) that the HVA may consist of a metamorphosed pile of volcaniclastic rocks.

Thin, 2-80 cm thick dikes of non-foliated pink pegmatite with aplitic borders irregularly cut the outcrop. These are typical of those associated with the NPG and are indicative of the northern extent of the intrusive.

A normal fault offsets a large xenolith in the HVA downward to the north a few meters in the center of the outcrop. This may have occurred during later stages of the HVA magmatic episode. A few late brittle faults with slickensides are also present.

Return to cars and continue N on I-95.

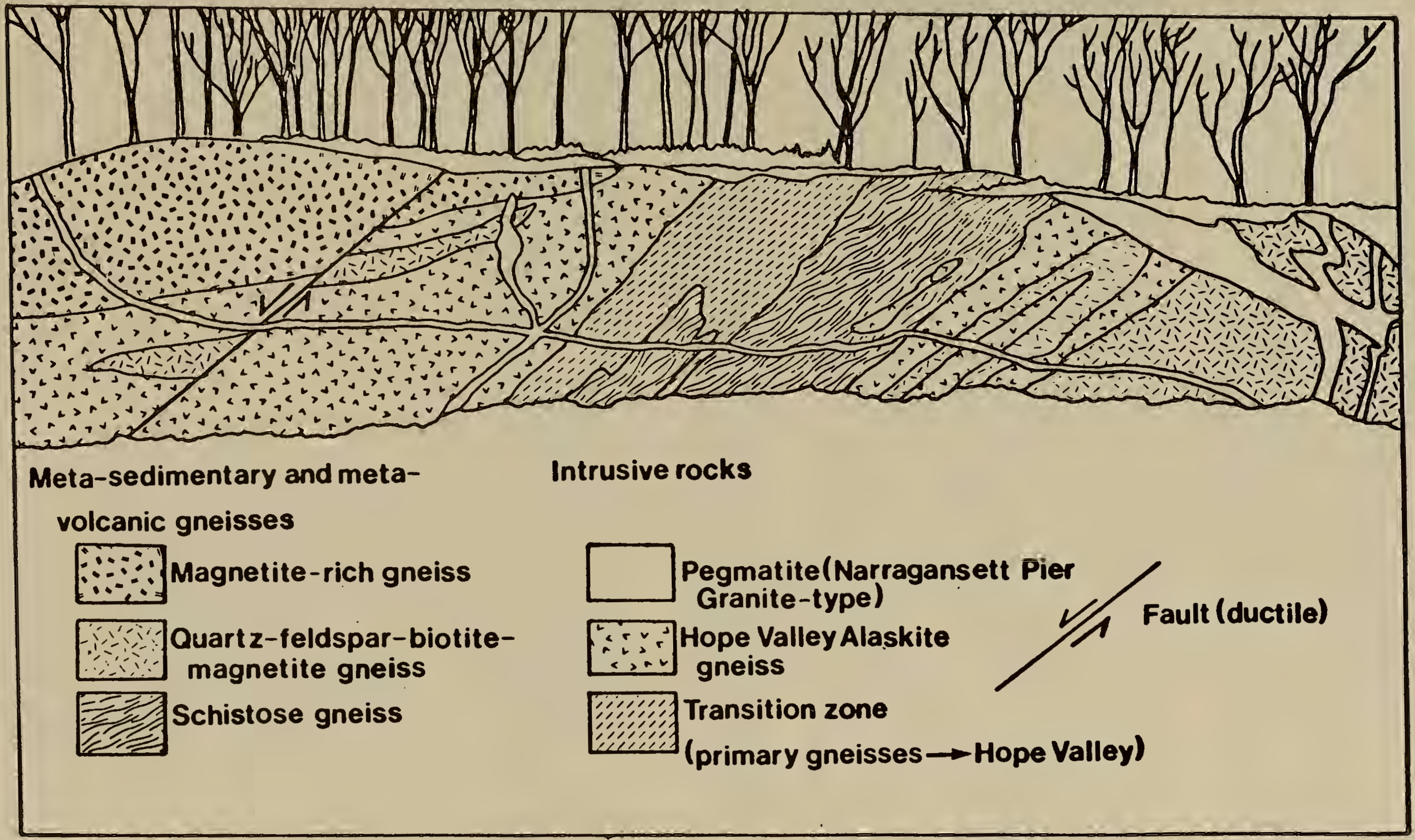

FIGURE 9. Geologic sketch of roadcut on southeast side of U.S. 95, miles north of R.I. Rt. 138, showing general rock types. View southeast (Stop 1).

cum.	int.	
12.3	1.3	Take exit 4 to stop sign; turn left onto US 3 South.
12.6	.3	Take left entrance ramp to I-95 South.
18.5	5.9	Roadcuts on both sides of highway near top of hill. Stop 2: TYPICAL HVA CONTAINING A FEW XENOLITHS OF BLACKSTONE AND CUT BY NPG. (Figs. 3 and 4).
		The HVA shows the typical rodding, that here is oriented nearly perpendicular to the face of the roadcut. Rock that may appear nearly massive on the outcrop face will appear strongly foliated when viewed from above. The non-foliated NPG is therefore difficult to spot on the face, but easily seen on the top. The NPG occurs as small sills, dikes and irregular patches that form 5 to 15 percent of outcrop. Examples of the more clearly seen dikes are 5 m south of the northern highway sign, where a north dipping dike (about 40 cm wide) occurs, and farther south about half way between the 2 signs, where a 2 to 2.5 m wide steeply dipping dike, with xenoliths of HVA, is present (Fig. 4). The later dike locally has very irregular contacts. This dike also contains minor biotite aligned parallel to the contacts indicating a very weak flow foliation.
		On fresh rocks both the HVA and NPG have similar light pinkish-gray color, but on weathered surfaces the NPG weathers slightly lighter whereas the HVA takes on a grayer hue, making distinctions easier.
		Here and elsewhere the general mineralogic similarity of the NPG and HVA, the manner in which the NPG is laced through the HVA and a few local highly irregular contacts and patchy occurrences suggest that the NPG may possibly have been derived from partial melting of the HVA at depth, and moved only a short distance before consolidation. Detailed geochemical studies may help resolve this possibility
		Return to cars and continue South on I-95.
21.0	2.5	Take exit 1 to US 3 South.
23.0	2.0	Turn left onto RI 216 South
25.4	2.4	Turn right, stay on RI 216 South at stop sign (intersection RI 91).
26.3	0.9	Turn left, stay on RI 216 South (RI 91 South continues straight).
27.6	1.3	Turn left onto Buckeye Brook Road (entrance to Burlingame State Park).
29.5	1.9	Turn left onto small dirt road into Burlingame Management Area (wooden sign to left).

cum. int.

30.0 0.5 First fork in road.

Stop 3: LARGE EAST-WEST-TRENDING DIKES OF NPG CUTTING HVA. (Fig.10). Foliation regular, approximately east-west-trending (part of structural block bounding Watch Hill Fault Zone on southeast side with regular east-west foliation, relatively few joints and relatively sparse dikes). Note also well-developed north-south jointing, prominent on aerial photos of this area.

Return to cars and follow left fork.

31.3 0.7 Road curves sharply right (north).

Stop 4: WATCH HILL FAULT ZONE.

Walk up gulley east of bend in road. HVA cut by more numerous intrusions of NPG and pegmatite. (Fig. 11) Very strong jointing - dominantly trending toward northeast. Part of large northeast-trending joint zone intruded by NPG.

34.4 3.1 Retrace route to RI 216, go right (N) on RI 216.

35.7 1.3 Turn left onto RI 91 W.

40.8 5.1 Follow RI 91 into Westerly; take right at first stop light onto US 3 N.

42.0 1.2 Take right onto entrance ramp to RI 78S (Westerly Bypass).

42.3 0.3 Large road cut.

Stop 5: NARRAGANSETT PIER GRANITE INTRUSIVE INTO AMPHIBOLITIC COUNTRY ROCK: NPG intruded by dike of Westerly Granite, and both granites cut by lamprophyre dikes that contain mantle-derived lherzolite nodules and megacrysts.

General field relationships exposed in the outcrop are illustrated in Figure 12. This is the only known place where NPG exhibits a simple intrusive relationship with the country rocks, as opposed to its more general lit-par-lit mode of emplacement. The contact with biotite amphibolite at the north end of the outcrop strikes N60°E and dips 60°N, and is slightly discordant with the foliation of the schist (E-W, 65°N). Granite is coarse-grained and unsheared next to the altered and friable amphibolite. The amphibolite is rich in biotite and muscovite, but locally has layers rich in hornblende, and less common garnet. Small aplites and pegmatites (one $\sim$1 m. wide) extend from the granite into the amphibolite where they locally cut foliation.

The dike of fine-grained Westerly Granite strikes E-W; the lower contact is somewhat undulatory, but subparallel to the upper contact, and dips 15-20°S. The contacts against NPG are unquenched, and commonly are characterized by discontinuous zones of pegmatite; commonly these pegmatites follow the contact for a short distance, and then abruptly cut into NPG or WG.

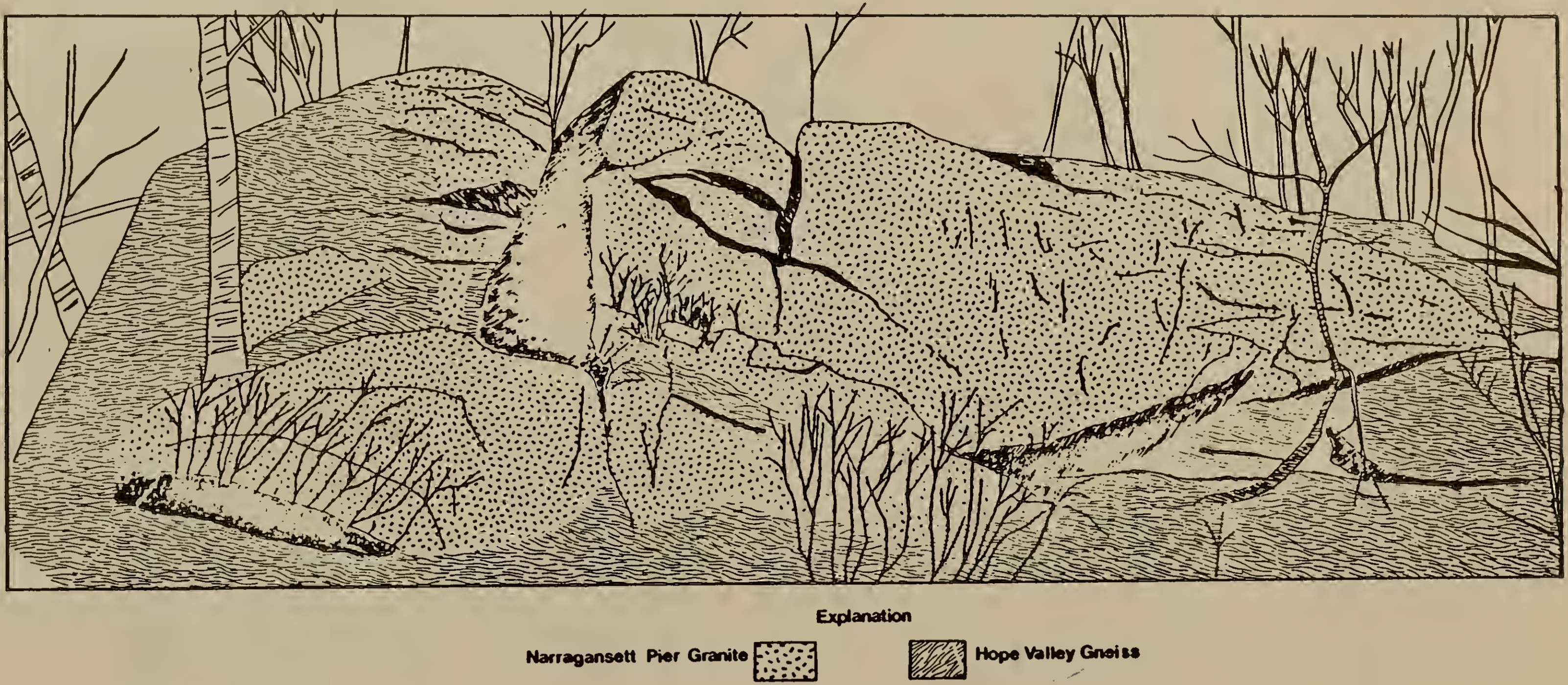

FIGURE 10. Geologic sketch of outcrop in Burlingame State Park, showing large like of Narragansett Pier Granite intruding Hope Valley Alaskite Gneiss. Foliation in gneiss trends east-west; northeast-trending joints are relatively absent. Pronounced north-south-trending joints. View north (Stop 3).

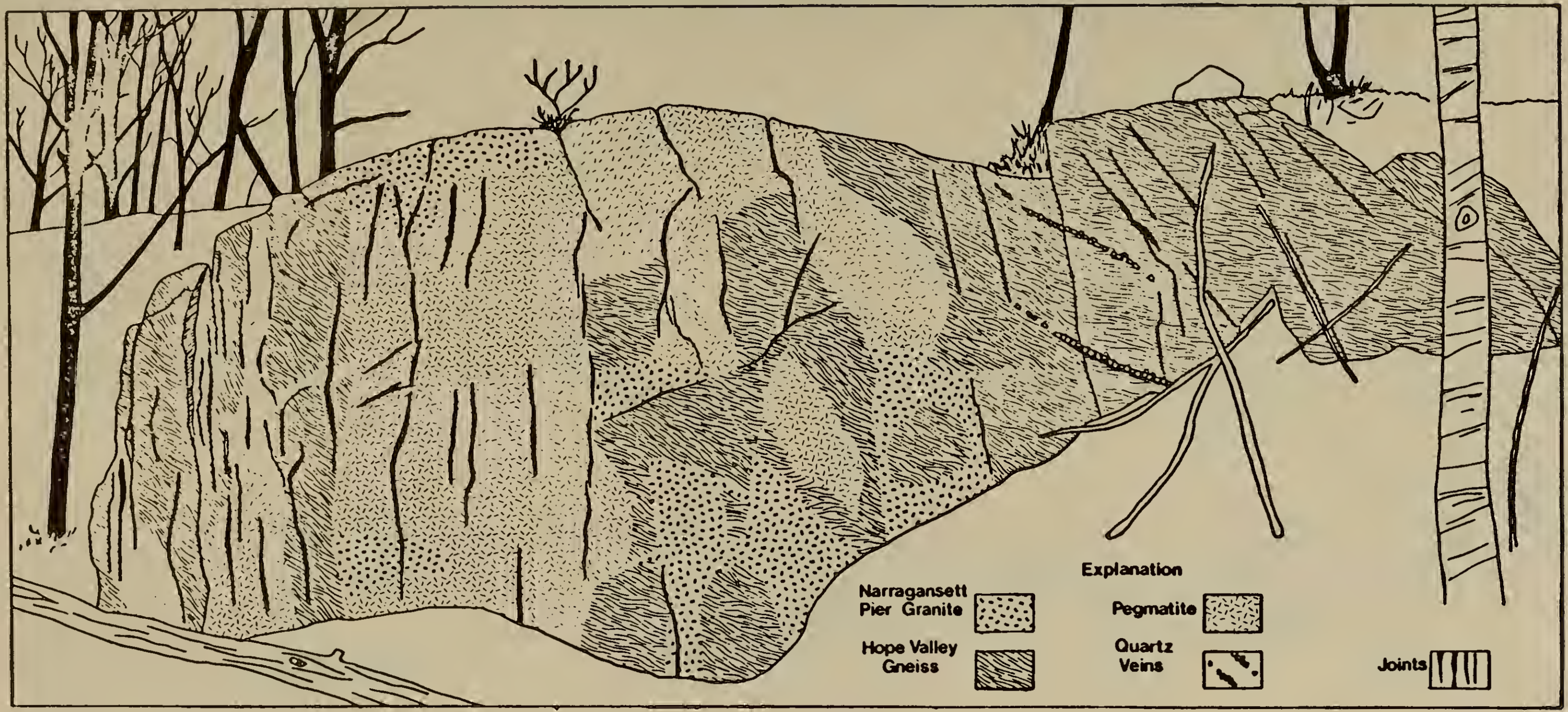

FIGURE 11. Geologic sketch of outcrop in Burlingame State Park in northeast-trending lineament zone extension of Watch Hill fault zone. Hope Valley Alaskite Geniss intruded by dikes of Narragansett Pier Granite and associated pegmatites. Northeast-trending joints, relatively absent outside zone, strongly developed within zone. View southwest (Stop 4).

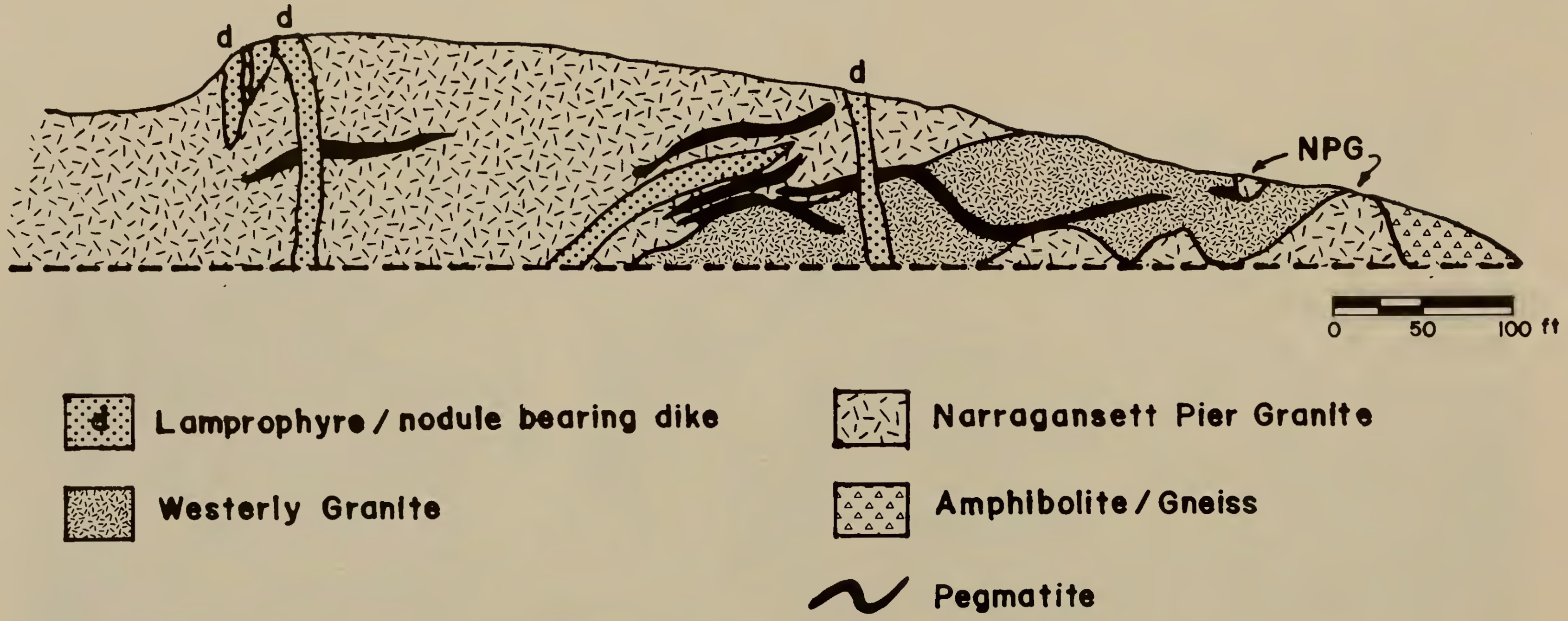

FIGURE 12. Generalized cross-section of Stop 5 road cut (west side) showing Narragansett Pier Granite intrusive into older amphibolitic gneisses. Westerly Granite cuts the NPG, and both granites are cut by lamprophyre dikes that contain lherzolite nodules (Stop 5).

cum. int. Two lamprophyre dikes that strike N 25° E with nearly vertical dips cut both the NPG and WG. The dikes are monchiquite (Leavy and Hermes, 1977, 1978, in press; Leavy, 1980), and are characterized by microphenocrysts of Ti-augite, kaersutite, olivine, phlogopite, titanomagnetite and apatite enclosed in a matrix of analcite, calcite, and a zeolite. Primary flow fabric parallel to contacts is common in the dike rocks, and ocellar textures are present that may indicate liquid immiscibility. In addition these rocks contain a variety of megacrysts (olivine, varieties of low Ti clinopyroxene, and ilmenites) and xenolithic nodules which include chrome spinel-bearing lherzolite, harzburgite, and wehrlite. Based on the mineral assemblages and pyroxene chemistry, Leavy (1979) and Leavy and Hermes (1977, in press) estimate that these nodules equilibrated at temperatures of 950-1200°C in a pressure regime between 9-25kb, clearly within the mantle.

Radiometric dating underway includes zircons from NPG and WG collected from this outcrop, as well as K-Ar dating of phlogopite and kaersutite from one of the lamprophyric dikes.

Return to cars and continue S on RI 78.

44.6 2.3 Take left at stop light onto US 1 N.

48.1 3.5 Intersection of US 1 and Scenic 1A south.

Break in road log for optional Stop 6A.

(0 .9) Go South on Scenic 1A, take left onto Noyesneck Road.

(1.9 1.0) Bear right onto Wawaloam Drive

(2.0 .1) Park on right on Fenway Road; walk south to outcrop on beach. Private property above mean high tide line.

Stop 6A: METASEDIMENTARY - METAIGNEOUS ROOF PENDANT WITHIN NARRAGANSETT PIER GRANITE. This large xenolith includes greenstone, calc-silicate rock, and other metasedimentary lithologies that probably correlate with units of the Blackstone Series.

Return to cars and continue on Wawaloam Drive.

(3.2 1.2) Turn right at stop sign onto Scenic 1A North.

(4.7 1.5) Intersection of US 1 and Scenic 1A.

Rejoins road log.

Continue N on US 1A.

49.9 1.8 Turn right onto West Beach Road (to Quonochontaug).

cum.	int.	
51.5	1.6	Turn left into private drive (just before line of mail boxes). Park at end of drive, walk south to outcrops on the shore. Private property.

<u>Stop 6</u>: PORPHYRITIC FACIES OF NPG

Much of the southern shoreline east of Westerly consists of sparse outcrops of a porphyritic facies of NPG. The contact relationships with other textural varieties is nowhere exposed, and it is not known whether the contact is gradational, intrusive, or faulted. The rock at this outcrop is typical of the porphyritic facies, and is characterized by euhedral phenocrysts of K-spar up to 5 cm enclosed in a finer but coarse-grained groundmass. This textural variety is modally and chemically similar to other textural varieties.

The outcrop is cut by N-trending (E dipping) aplitic and pegmatitic dikes as well as by subparallel, lenticular lenses of quartz. Some of the aplites exhibit a crude flow layering as evidenced by the alignment of biotite, and in some cases they have been stretched and disjointed and invaded by granite, indicating that the granite was still plastic and mobile at the time of dike intrusion. At least one E-W trending slickensided fault cuts the outcrop.

Several large glacial erratics of orbicular granite were found along the coastline approximately ¼ mile west of this outcrop. One is in the British Museum of Natural History, and a second is in the rock garden of the URI Geology Department. The latter shows the contact of the porphyritic NPG facies against the orbicular rock, which has the same mineralogy as NPG (see description in Kern, 1979). The occurrence of an orbicular-textured rock in this area as well as the porphyritic facies may indicate that a shallower part of the intrusion is exposed here as compared to the deeper seated exposures to the east in Narragansett.

Return to cars and retrace route on West Beach road to US 1 North.

53.1	1.6	Turn right onto US 1 North.
67.1	14.0	Take RI 108 exit (to Narragansett - Point Judith); turn right at stop sign onto South Pier Road, and continue straight through stop light.
68.9	1.8	Turn right onto Ocean Road (Scenic 1A South).
69.8	.9	Turn left onto Newton Avenue.
69.9	.1	Park at end of street, walk to outcrops along the coast. BE CAREFUL of slick, algae-covered black rocks.

cum. int.

Stop 7: PINK FACIES OF NPG

Equigranular, coarse-grained NPG typical of the NPG is exposed at this outcrop; it is in sharp contrast to the white facies to be seen at the next two stops. Cross-cutting aplites and pegmatites along these coastal exposures appear to consist of three different age groups as summarized in Figure 6.

Return to cars and return to Ocean Road.

70.0 0.1 Turn right onto Ocean Road

71.6 1.6 Take left onto Exchange Street, just past the "Towers" (building that straddles Ocean Road); Exchange Street becomes Kingstown Road.

72.2 0.6 Take left at stop light onto Narragansett Avenue.

72.5 0.3 Take right onto Mumford Road (just past tennis courts).

73.1 0.6 Park to right on Peckam Road. Walk to Mumford Road and down hill to outcrop in back of house. Private property.

Stop 8: INJECTION ZONE OF WHITE GRANITE FACIES OF NPG.

The white granite here is in sharp contrast to the typical pink facies seen before. The white facies is restricted to zones near contacts where the country rock contains carbonaceous- and graphite-rich layers. We interpret this to mean that the carbon in the metasediments kept fO_2 in the melt relatively low, and iron was kept mainly in the +2 state. Compared to the pink granite, the white facies is richer in muscovite, lower in biotite, contains locally abundant Mn-rich spessartine garnet, and is free of magnetite or other opaque minerals.

The outcrop consists of a lit-par-lit layered sequence of white granite injected into sandy metasediments. The metasediment contains the assemblage garnet-biotite-muscovite-plagioclase-microcline-quartz, and is enriched in biotite adjacent to the granite. The granite is not quenched against the metasediment, nor is there evidence of contact metamorphism in the area (Kocis, 1981; Milne, 1972), indicating that the country rock was hot at the time of intrusion. This injection zone can be traced northward along strike for ¼ mile, whereupon the proportion of granite to metasediment generally decreases.

The granite generally parallels the foliation of the metasediments, which is complexly folded, but locally cuts across and truncates layers, and in a few instances exhibits injected ptygmatic folds. in many respects, the outcrop is typical of an injection migmatite The lit-par-lit nature of the contact generally is representative of the contact wherever exposed.

cum.	int.	
		Return to cars and backtrack on Mumford Road to Narragansett Avenue.
73.7	0.6	Take left onto Narragansett Avenue.
74.3	0.6	Take left at second stop light, then bear right.
74.5	0.2	Take left at stop light onto Scenic 1A north.
75.7	1.2	Turn right onto Old Boston Neck Road.
76.0	0.3	Turn right into private drive; continue 0.2 miles to house on left and park along drive. Private property. Outcrops form Cormorant Point along the coast line.

Stop 9: LAYERED WHITE-GRANITE FACIES OF NPG OF CORMORANT POINT

The white facies exposed here exhibits a locally prominent igneous layering characterized by parallel to subparallel layers of alternating textures (Fig. 13). Equigranular, medium-grained granite alternates and is interlayered with a fine-grained aplitic rock and with a coarse, pegmatitic textured rock. Locally the layering is more obvious than in other areas. The best places to observe it are on the island (accessible at low tide) and along the SW exposures of the point. A relatively thick, homogeneous fine-grained granite layer rich in garnet has been mapped separately.

Numerous xenoliths that comprise screens of metasediment are included in the layered white granite. These schistose rocks range in lithology from sandstones to conglomerates. Of importance is the fact that the lengths of these screens as well as their foliations are nearly all parallel and lie in the plane of layering of the granite. Moreover, the foliations are conformable to the foliations in the schists that constitute the country rock to the north. We interpret those features to mean that the granite was injected in this zone as a series of pulses that passively invaded the country rocks, preserving screens of generally unrotated metasediment. The diverse granite texture probably reflects local and temporal variations in H_2O pressure which resulted in grain sizes ranging from aplitic-pegmatitic.

Some xenoliths exhibit local folding and deformation, implying that they were deformed prior to granite emplacement. Some contain biotite enriched zones adjacent to the granite, and in some cases, garnet in these zones can be traced away from xenolith tails to form diffuse garnet trains in the granite. This suggests a certain amount of local assimilation and reaction with the granite. In addition some xenoliths have graphite-rich layers, and Stephanian B plant fossils have been identified from carbonaceous layers from one xenolith (Brown et al., 1978).

Return to cars and retrace route to Scenic 1A. To return to the University of Rhode Island, take right on Scenic 1A; take left onto RI138 W (about 4 miles); continue W for approximately 6 miles to Kingston.

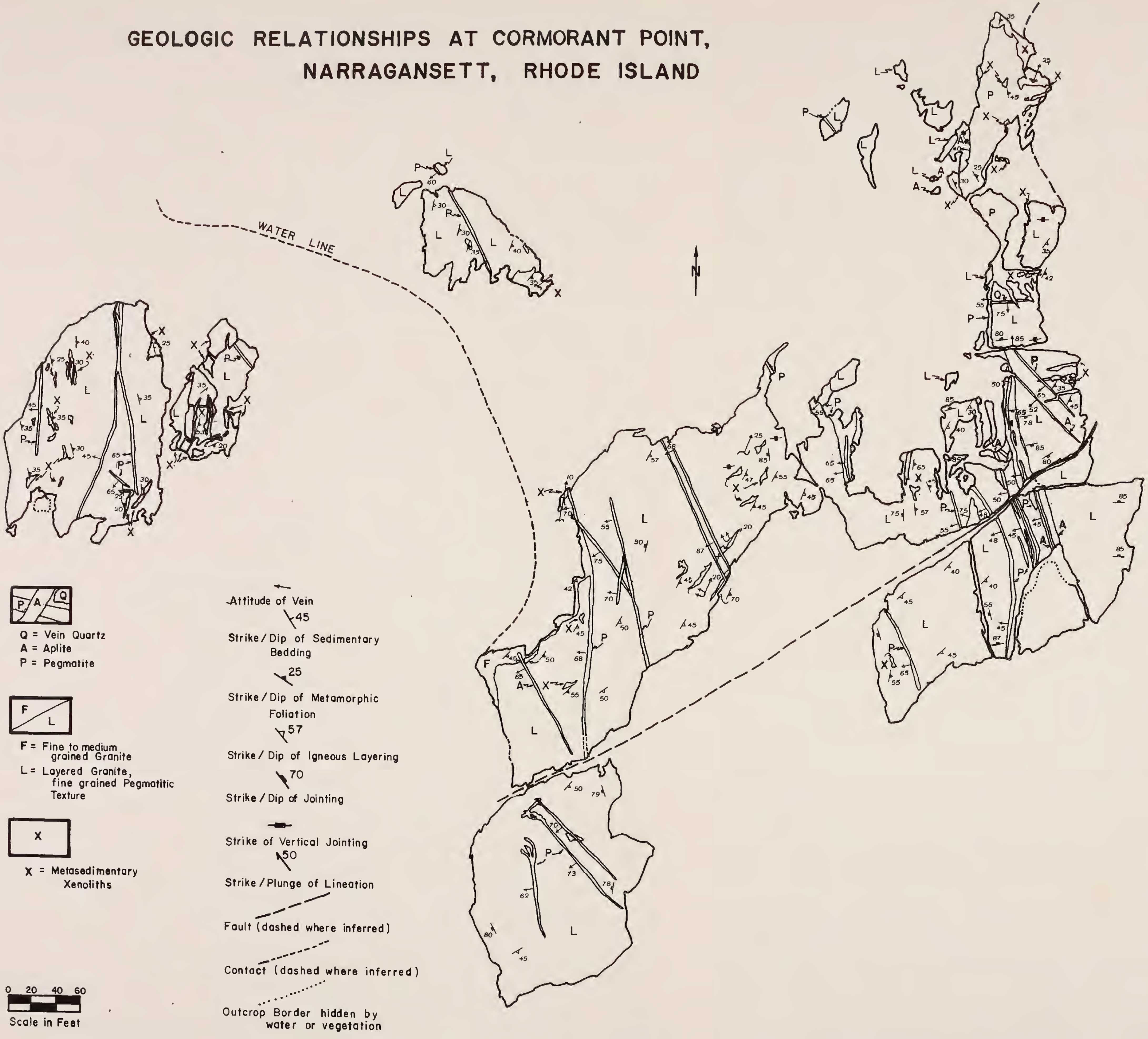

Figure 13: Geologic relationships at Cormorant Point (Stop 9).
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Field Guide
to
Coastal Environmental Geology
of
Rhode Island's Barrier Beach Coastline

by
John J. Fisher
Department of Geology
University of Rhode Island
Kingston, RI 02881

Introduction

The Rhode Island southern coastline, 30 km in length, can be classified as a barrier beach complex shoreline. Developed from a mainland consisting primarily of a glacial outwash plain, it has been submerged by recent sea level rise. Headlands (locally called "points") composed of till and outwash plain deposits separate a series of lagoon-like bays (locally called "ponds") that are drowned glacial outwash channels. Interconnecting baymouth barriers (locally called "barrier beaches") with several inlets make up the major shoreform of this coast (Figure 1).

This field guide is an introduction to the coastal environmental geology features of the Rhode Island barrier beach coast. Recently funded Sea Grant research by the author allowed support of a series of regional inventory studies of various coastal geomorphic and sedimentalogical features along the entire

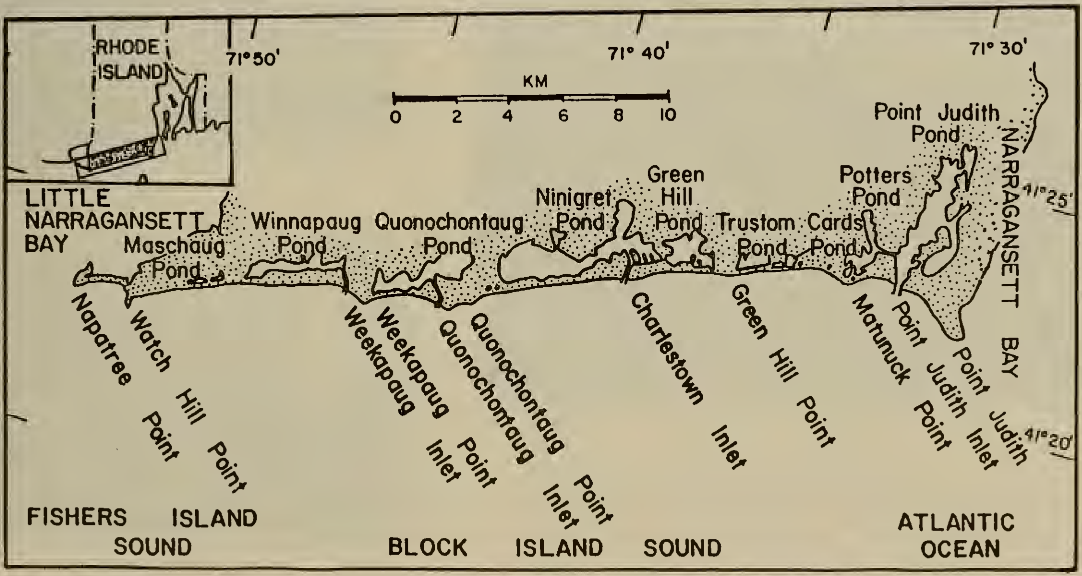


Figure 1. Rhode Island southern barrier beach shoreline from Napatree Point to Point Judith. Mainland headlands locally referred to as "points" and inlets as "breachways".

Plate 1. View eastward of Rhode Island's barrier beach coastline, 30 km in length, extending from Watch Hill Pt. (west) to Point Judith (east). Entire coast mapped as eroding during 1939-1975 period. Headlands (called "points") are composed of till and separate the barrier beaches. (Photographs - J. Fisher)

Pl.2 Charlestown Beach erosion

Pl.3 Wreck exposed on beach

Pl.4 Dune scarp erosion

Pl.5 Exhumed tidal marsh peat

Rhode Island coast. Long-term (1938-1975) beach and dune erosion was mapped as was washover and tidal inlet deposition. Short-term regional beach and dune profiles and sequential beach sediment inventories were also conducted. Regional short-term and long-term inventories of this nature are especially useful in coastal management and environmental impact studies (Fisher, 1979). This guide presents some of the results of the above studies as well as general Rhode Island coastal information.

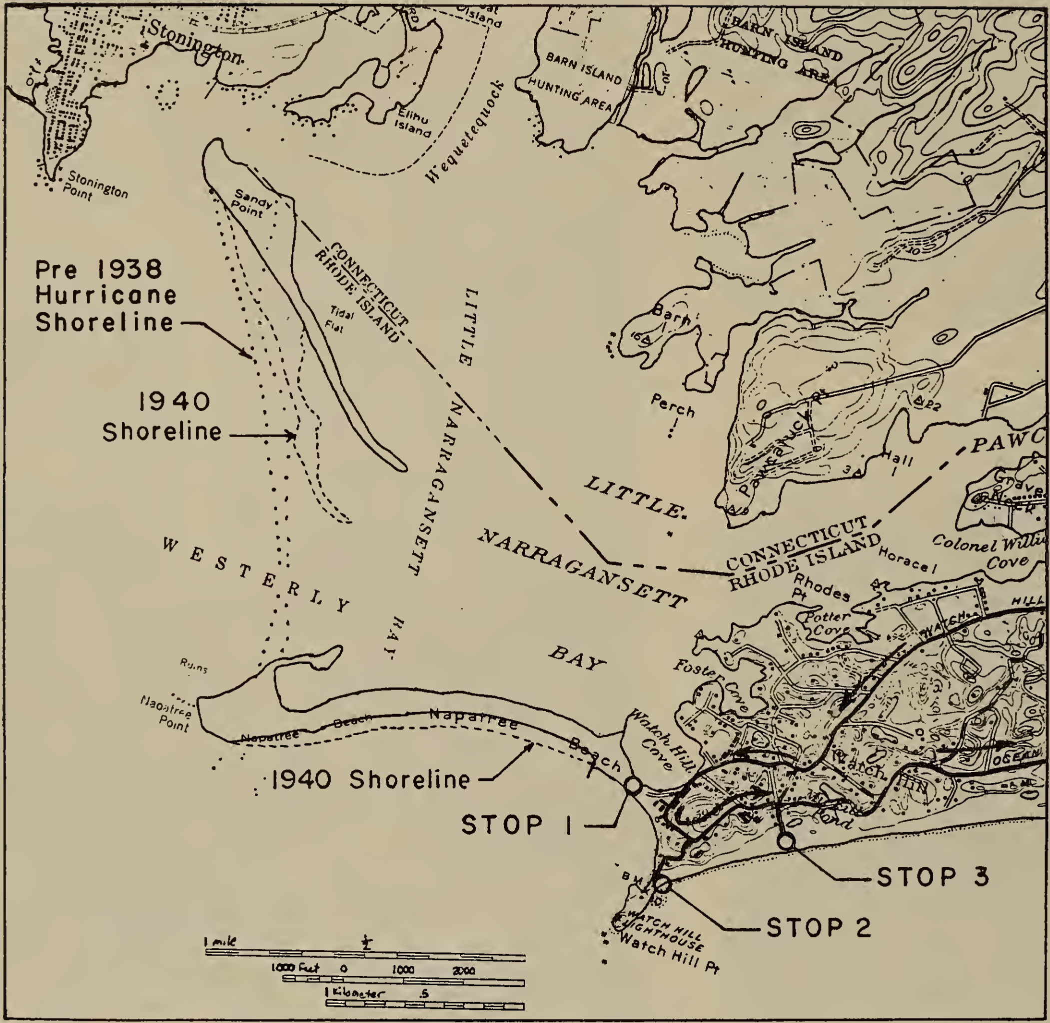
The trip log extends from Watch Hill to Point Judith, R. I., and can be covered in one day. All the indicated stops are at public parking spaces. Fees may be charged at some parking lots and beaches during the summer season. Be respectful of private property. Do not walk on dune vegetation if at all possible. In the text "map" refers to the topographic quadrangles indicating the route, while "figure" refers to the data diagrams. "Plate" refers to the photographs at the beginning of the trip log. Mileage starts from the University of Rhode Island at Kingston.

Road Log - URI to STOP 1

0.0 Intersection of Rt. 138 and Keany Gym Rd. (for Lower College Rd. add 0.4 and for Upper College Rd. add 0.6)
0.7 Turn left at the stop light on Rt. 110 (Ministerial Rd.)
1.5 On right Larkin Pond (glacial kettle hole lake)
2.7 Continue up Tefft Hill (roche moutonee)
4.6 Cross Worden Pond Rd. (state's largest natural waterbody to west)
5.2 Climb Charlestown recessional moraine
6.7 Cross US 1A - Old Post Rd. (glacial outwash plain)
6.9 Turn right on US 1 (4-lane divided highway travels on outwash plain with moraine to right)
14.1 View to left of Ninigret Pond and barrier beach, to right is Charlestown recessional moraine
17.7 Continue on US 1 bearing to right
19.1 Continue thru stop light on US 1
21.2 Turn left on Airport Rd. at stop light (on right is Rt. 78)
22.4 Continue straight ahead at intersection
22.6 Turn left to Watch Hill at stop sign
23.2 View to right of Pawcatuck River
23.6 Keep left on road at arrow
25.5 Bear right on road at intersection
25.9 Turn right into Watch Hill parking lot, STOP 1

STOP 1. Watch Hill - Napatree Beach (Map 1) - The extensive beach extending westward from the town of Watch Hill is Napatree Beach (Pl. 1). It is a tombola coastal form, by which the sediment which forms this beach had its source from both the Watch Hill area and Napatree Point. Sand eroded from both these glacial deposits is moved by longshore currents from the east and west respectively. A groin has been built to trap this west moving sediment. Mapping from aerial photographs indicates that this entire beach has migrated landward almost its entire width, some 200 feet, since 1940 as diagrammed on Map 1. A pier that was formerly on the bay side (Little Narragansett Bay) can now be seen emerging from under the sand on the present foreshore.

Prior to the September 21, 1938, hurricane Napatree Beach was covered with summer homes. They were all washed away by this record hurricane. Hurricane waves 30 feet high were driven by a wind that reached 121 mph in mid-afternoon. In the Westerly - Charlestown shore area 118 were dead or



Map 1 - Stop 1, Napatree Beach, Watch Hill; Stop 2, Watch Hill Lighthouse; Stop 3, Niantic Ave. Beach (Mystic, Watch Hill Quad.).

missing and 312 in the entire state. Debris from hundreds of summer homes was carried by storm waters a half mile inland with damage of $100,000,000. along the Rhode Island shore. Wave damage was high because the greatest winds were on a spring high tide and, with the hurricane center to the west in Connecticut, counter-clockwise winds drove the water on the shore and up Narragansett Bay. Flood waters were 6 feet deep in Providence as it rose 13 feet above mean high water. This storm flood height is now the "design" height for all flood protection structures. In the morning of August 31, 1954, Hurricane Carol, striking under similar meteorological conditions, caused $200,000,000. damage, but with some warning only 19 died.

Before the 1938 hurricane, what is now Sandy Point island, north of Napatree Point, was connected as a spit to the Point at its southern end. Hurricane waves formed a large inlet at the spit base (Nichols & Marston, 1939) which remains open to this day. Since 1940, this southern end of the new island has rotated to the east as diagrammed on Map 1. A former military fort on the high ground of Napatree Point has survived both hurricanes and is still present.

25.9 Turn right leaving Watch Hill parking lot
26.0 Turn left at flying carrousel onto Larkin Rd.
26.1 Caution. Turn right between two rock pillars on narrow, unmarked, Light House Rd. near crest of hill and continue ahead to gate watching for bumps
26.3 Park at Light House gate, STOP 2

STOP 2. Watch Hill Lighthouse (Map 1) - From the entrance to the lighthouse base, one can look landward to the west (left) and see the expanse of the Napatree Beach - Napatree Point tombola. The higher ground of Napatree Point, composed of glacial till, is obvious. More significantly, the view to the east (right) shows the prominent Watch Hill sea cliff. This cliff, 50 feet high, is the result of wave action from both the south and southeast eroding the Charlestown recessional moraine. This moraine, which on Long Island forms Orient Point, to the southwest continues as a series of linear islands, Plum Island (3 mi), Gull Islands (1 mi) and Fishers Island (6 mi) to Watch Hill Point. Post-glacial meltwater erosion by the Connecticut River is responsible for the dismembering of this moraine ridge into a series of islands. The Charlestown recessional moraine trends inland some 1 - 2 miles (Pl. 1), and then parallels the Rhode Island coast just north of US 1 (Old Boston Post Road) for 20 miles. It finally disappears into the waters of Narragansett Bay just west of Point Judith Pond. It reappears to the east as the Elizabeth Islands and Cape Cod. Looking southeast on a clear day, Block Island, 10 miles offshore, is a remnant of the same Wisconsin terminal moraine. It starts from Montauk Point on Long Island to the west and makes up Martha's Vineyard and Nantucket Island to the east. Again post-glacial drainage down Narragansett Bay and the Sakonnet River is responsible for the dismembering of the moraine ridge into these offshore islands.

An excellent example of the revetment type sea wall structure necessary for storm wave protection can be observed along the base of the Lighthouse Road and the base of Watch Hill sea cliff. These blocks are composed of the pink Narragansett Pier Granite which underlies the entire Rhode Island south shore from Westerly to Point Judith. These particular ones are probably from the granite quarries in the Westerly area just north of Watch Hill.

26.6 Retrace route and turn right on Larkin Rd.
26.7 Bear left around the yellow Ocean House Hotel and immediately turn right down Everett Rd.
26.8 Park at Niantic Beach (or along Niantic Ave.), STOP 3

STOP 3. Niantic Avenue Beach (Map 1) - At this beach, the view to the west shows the impressive Watch Hill sea cliff. To the east is the beginning of the Rhode Island barrier beaches. Behind the frontal dune is a series of ponds that are probably the remnants of once larger ponds (Pl. 1). The geomorphic cycle of development of the Rhode Island barrier beach is the furthest advanced at this beach. In the past, this beach was probably further offshore, perhaps with an inlet leading into a larger saltwater pond. With time, the beach has migrated landward almost to the head of this former salt pond. Marsh deposits fill much of this former larger pond.

The rate of retreat of this former barrier beach and other barrier beaches along the Rhode Island shoreline can be determined by detailed photogrammetric mapping. Vertical aerial photographs from 1939 (earliest

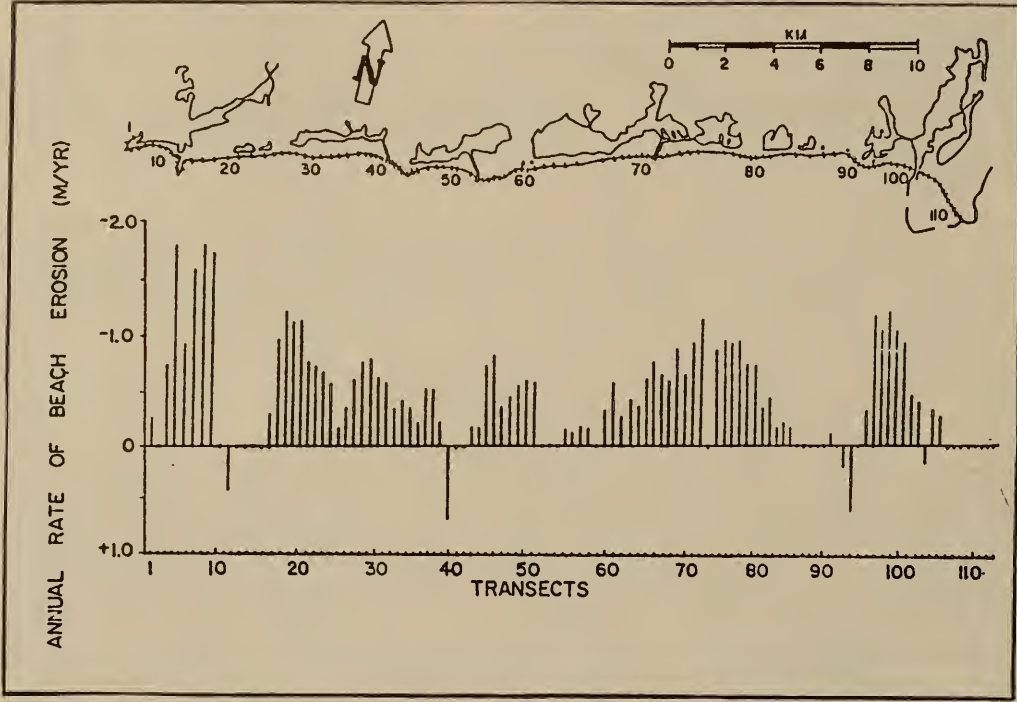
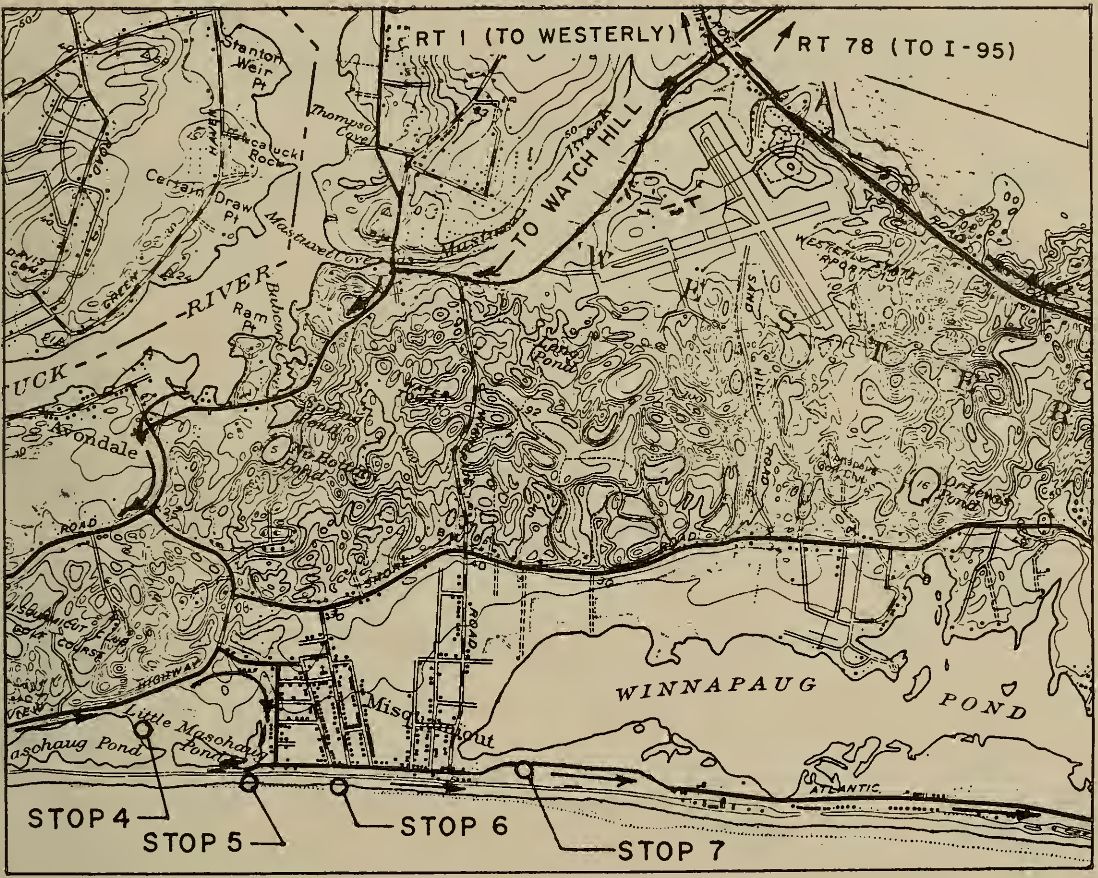


Figure 2. Annual rate of Rhode Island beach erosion in meters per year based on photogrammetric mapping for 1939-1975 period. Coast completely erosional except up-drift from inlet jetties. Average rate of erosion is 0.2 m/yr (Fisher & Simpson, 1979).

coverage) to 1975 (most recent at time of study but 1980 coverage now available) are studied to determine the high tide line. Surveyed field control points are established on each photograph for scale and to reduce distortion. Distortion is eliminated by optical rectification in a Bausch and Lomb Zoom Transfer Scope. This scope, designed for satellite interpretation, has been modified for use in these studies by the author. These mapped shoreline changes are calculated using a digital planimeter and presented as areal changes per unit shoreline of 1000 feet (Fisher, 1981, 1979).

Based on these studies, the annual rate of change for the Rhode Island shore for the period 1939-1975 has been completely erosional (Figure 2). The only accretion is immediately up-drift (to the west) from jetties at each of the four inlets. The dominant direction of drift along the Rhode Island coast has been said to be from west to east (McMaster, 1960) and this data support that interpretation. The average annual rate of beach erosion is 0.2 m/yr, however along this section of beach the erosion is above average and is from 0.8 to 1.0 m/yr (Fisher & Simpson, 1979).

26.8 Turn onto Niantic Ave.
27.1 View to right of recessional moraine and Light House
27.2 At stop sign at intersection bear right on Yosemite Valley Rd.
27.4 Bear right at y-intersection onto Ocean View Highway
28.2 Park off road on right at Maschaug Pond just before Golf Course, STOP 4



Map 2 - Stop 4, Maschaug Ponds; Stop 5, Misquamicut Headland; Stop 6, Misquamicut Town Beach; Stop 7, Misquamicut State Beach (Watch Hill Quadrangle).

STOP 4. Maschaug Pond (Map 2) - Park along the road on the right and climb the low embankment. This stop overlooks Maschaug Pond to the right (west) and the Misquamicut Club Golf Course to the left (east). Maschaug Pond is managed by the Rhode Island Audubon Society as a wildlife refuge area. Do not go into the area unless permission is given by the R. I. Audubon Society as you may disturb nesting migratory waterfowl and shore birds.

From this embankment one can clearly see that the beach beyond Maschaug Pond has numerous washover fans that extend from the beach, through the foredunes, to the edge of the pond (Pl. 1). Washovers develop when a storm surge overtops the frontal dune and barrier beach. This entire backbarrier shoreline has a characteristic bulbous fan shape on maps or aerial photographs that identify it as a prominent washover beach. Photogrammetric mapping of washover accretion for the period 1939-1975 was conducted of the entire Rhode Island shoreline (Fisher & Simpson, 1979) using the same techniques developed for mapping beach erosion (see Stop 3 for discussion). Along this Maschaug Pond barrier beach, more than 78,000 m^2 of supratidal and nearly 58,000 m^2 of subtidal washover deposits have been deposited from 1939-1975. All the Rhode Island "ponds" have very low tidal ranges and thus little intertidal deposits. Most of this overwash was deposited in

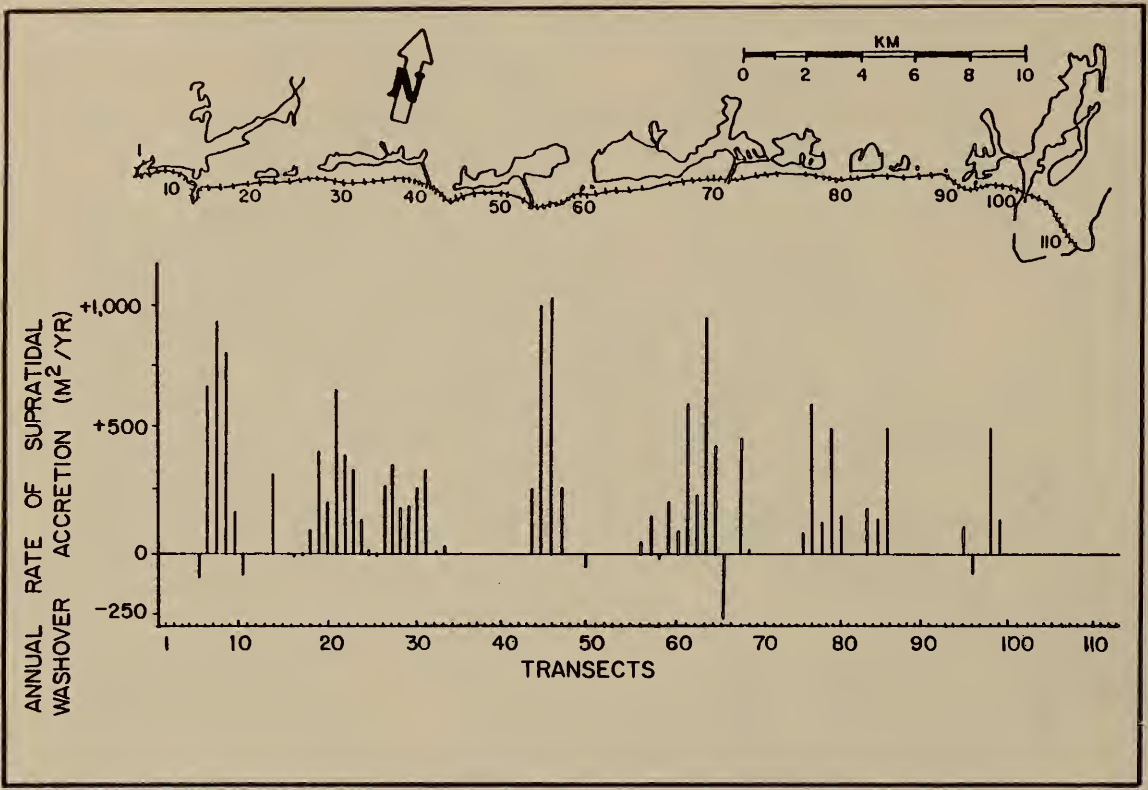


Figure 3. Annual rate of supratidal washover accretion in meters per year based on photogrammetric mapping for 1939-1975 period. Washover is more common along western half of Rhode Island coast (Fisher & Simpson, 1979).

the western portion of Maschaug Pond. In general, for the entire Rhode Island coast (Figure 3), washover deposition is more common along the western half of the coast. This is probably because the barrier beaches are further along in their cycle of development and more prone to overwash.

28.2 Continue on Ocean View Highway
28.6 Turn right on Bayberry Ave.
28.8 Turn right on Maplewood Ave.
29.1 Turn right at the stop sign on Atlantic Ave.
29.2 Park just past where the road becomes dirt at Misquamicut Pt. Beach, STOP 5

STOP 5. Misquamicut Point Beach (Map 2) - This beach, just adjacent to the western side of the Misquamicut "Point" headland exhibits excellent washover deposits. The pond just inland is Little Maschaug Pond and just beyond the Golf Course to the north can be seen the Charlestown recessional moraine trending inland.

Along this beach, washovers cross the dirt road and extend completely to the marsh beyond. Overwash usually occurs at low points in the foredunes such as a blowout, former overwash channel or beach buggy access road and produces a distinct washover fan. If the entire foredune is low and there is a hurricane storm surge, a coalescing sheet-like washover, called a washover ramp, forms. The greatest factor controlling the occurrence and amount of washovers in the 1939-1975 period is the presence of an eroding beach. At 27% of the coast where washovers were above average, beach erosion was also greater than average. At 66% of the coast where washovers had occurred, beach erosion was also occurring.

During the 1938 hurricane, overwash surges eroded the barrier dunes, depositing "great scallops of sand which extend out over the marsh as much as 750 feet from the eroded foredune" (Nichols & Marston, 1939). Prevailing winds on the R. I. coast are from the SW, W and NW. Storm winds approach from all directions except the southwest, with the northwest favored for duration and velocity. Southeast winds are rare but are the most severe when they occur. Medium (2.0-4.0 m) and high (greater than 4.0 m) wave swells are predominantly from the east but low swells from the NE, SE, S and SW are common.

29.2 Turn around and proceed along Atlantic Ave.

29.5 Park on right at public access to beach west of Hotel Andrea on right opposite Crandall Ave., STOP 6

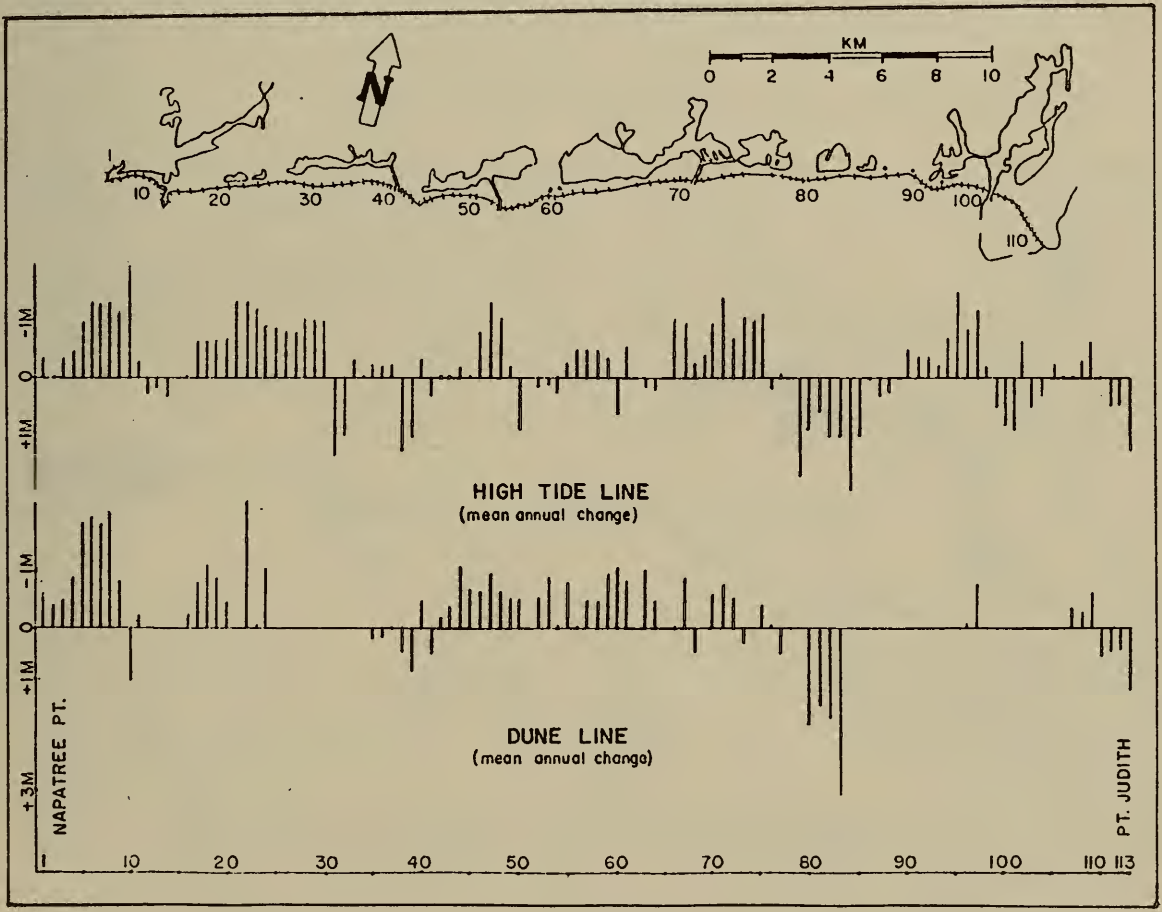


Figure 4. Annual rate of dune line erosion along Rhode Island coast in meters per year based on photogrammetric mapping for 1939-1972 period. Rate and pattern of dune line erosion similar to beach erosion for the same period (Fisher & Regan, 1977).

STOP 6. Misquamicut Town Beach (Map 2) - The town of Misquamicut is a very popular beach for day visitors, many coming from the inland Connecticut cities. Always a highly commercial developed beach, after the 1938 hurricane, of 500 summer homes, only 5 were left undamaged. Because of the low or absent frontal dunes along this beach, property owners have tried to protect their property in various ways. At the Andrea Hotel, east of the right-of-way, an artificial barrier dune was constructed in 1964 to protect the ocean front of the hotel from wave erosion. A unique feature was that several dozen scrap automobile bodies were incorporated as the core of this frontal dune. In the winter of 1966, severe wave erosion uncovered these autos, but beach and dune surveys indicated there was less erosion of the unconventionally constructed foredunes than of the adjacent beach front dunes. Inspection of the dune face often does not show any evidence of the interior auto bodies.

A regional survey of beach and dune erosion along the Rhode Island coast (Fisher & Regan, 1977) indicates an interesting relationship. Both the high tide shoreline and dune edgeline were mapped photogrammetrically for the period 1939-1972 (Figure 4). As mentioned earlier, most of the R. I. shoreline is erosional, but the sand eroded from the high-tide shoreline has not gone into dune building. The survey shows that the entire coast's duneline's seaward edge was also in retreat. In general, the regional pattern and rate of shoreline retreat and advance is duplicated in the pattern and rate of the frontal barrier duneline.

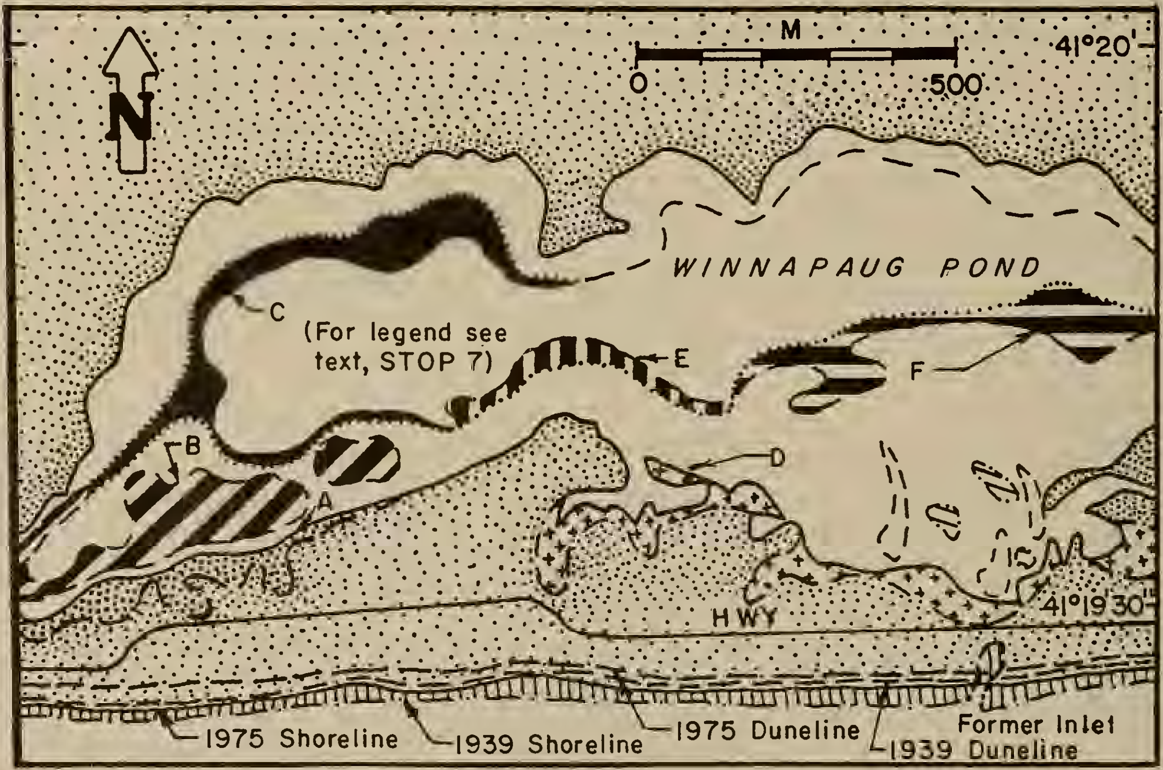


Figure 5. Western half of Winnapaug Pond and Misquamicut Beach indicating changes (1939-1975) in beach and dune line as well as subtidal and supratidal washover and tidal delta deposits. Changes mapped photogrammetrically (Fisher & Simpson, 1979).

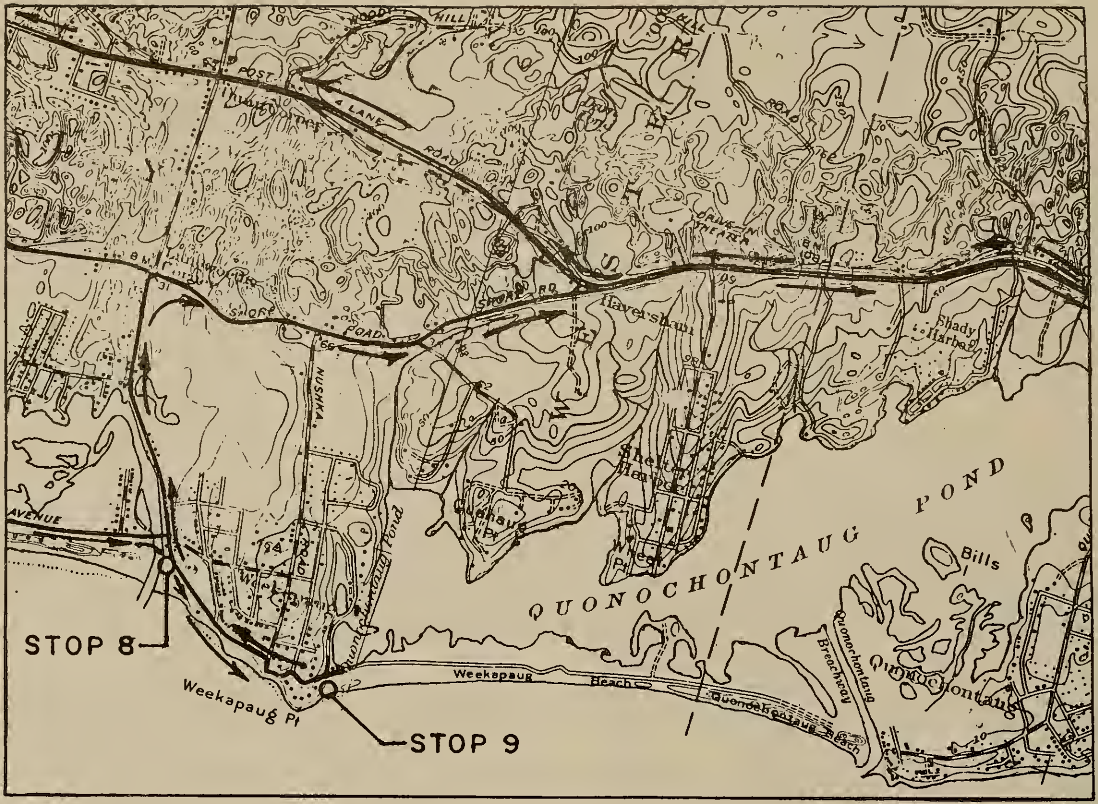
29.5 Continue on Atlantic Ave.
30.0 Park on right at Misquamicut State Beach parking lot, STOP 7

STOP 7. Misquamicut State Beach (Map 2) - The extensive parking lot for the state beach was developed by diverting the original beach road north, onto the back barrier area, and then back to its original course. The former back barrier area is then paved for parking (Pl. 1). Misquamicut Beach, together with Winnapaug Pond behind it, is an example of the beach and dune erosion, as well as the backbarrier changes over the period 1939-1975 (Figure 5). The changes were mapped photogrammetrically from aerial photographs (Fisher & Simpson, 1979). Along the western backbarrier area there was an increase in supratidal washover (A) but decrease in the area of subtidal washover (B). Subtidal washover did increase along the far margin of the pond (C). Along the eastern part of the pond, as shown and nearer Weekapaug Inlet, supratidal tidal delta deposits increased (D) along the backbarrier margin. In the center of the pond subtidal delta deposits increased (E) while to the east the subtidal delta deposits decreased (F). Areas not marked with a pattern showed no change. For the regional inventory, the entire oceanic shoreline and backbarrier ponds and inlets of the Rhode Island southern coast were mapped photogrammetrically and the areal changes calculated for the period 1939-1975 (Fisher, 1981).

32.1 Proceed on Atlantic Ave. (to right dunes rise to 35')
32.4 Cross bridge over Weekapaug Breachway and at intersection and stop sign turn right on Wawoloam Dr.
32.5 Immediately turn right into parking area of Weekapaug Fishing Area, STOP 8

STOP 8. Weekapaug Breachway (Map 3) - The bridge over Weekapaug Breachway, constructed in 1936, replaces earlier bridges constructed in 1918 and 1898. They replaced an earlier wooden toll bridge, 1/3 mi upstream, constructed in 1880 to haul seaweed for commercial purposes. The extensive stone jetties, revetment and facing along the breachway is necessary to stabilize the inlet channel. In general, if the Rhode Island inlets were not stabilized by jetties, they would probably be closed by longshore sedimentation. All the inlets are at the eastern end of their ponds, migrating to that position under the west to east longshore current. Since they cannot migrate any further, the sediment carried by the longshore current would probably be transported into the inlet, deposited as a flood tidal delta deposit and shoal the inlets closed. Long-term (1939-1973) photogrammetric mapping (Fisher & Simpson, 1979) of flood tidal delta accretion at the four Rhode Island inlets was conducted to determine the volume of sediment deposited behind each inlet (Figure 6). Flood tidal delta deposition together with washover accretion are the two main processes that move sediment landward. The Rhode Island coast is a microtidal coast with the mean tidal ranges varying from 0.76 m at Watch Hill to 1.07 m at Narragansett and the extreme spring tide range is 0.94 m at Watch Hill to 1.34 m at Narragansett (NOAA Tide Tables). Flood tidal deltas on microtidal coasts are generally poorly developed, although better developed than the ebb tidal deltas.

The Weekapaug Breachway flood tidal delta consists of large subtidal lobes with a sinuous channel and widespread supratidal vegetated deposits. The subtidal delta shoals have extended much further into the pond from 1939 to 1976, due probably to construction of the jetties and channel dredging between 1951 and 1963. This may have increased the inlet flow velocities and a larger amount of sediment was transported through the inlet.



Map 3 - Stop 8, Weekapaug Breachway; Stop 9, Weekapaug Point (Watch Hill Quadrangle).

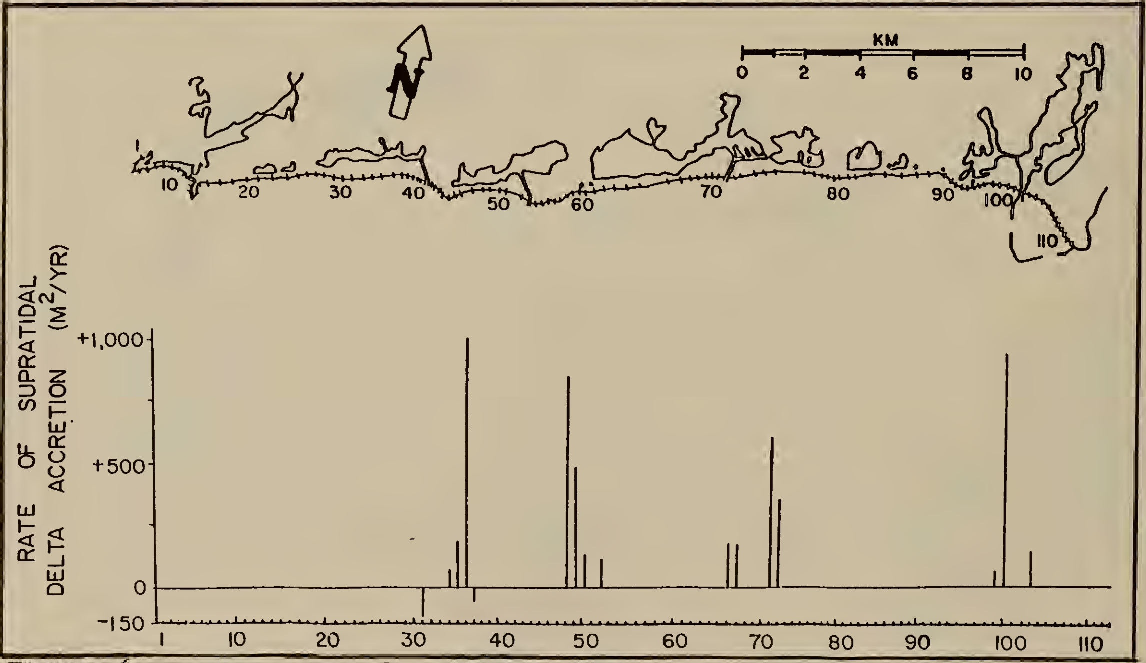


Figure 6. Annual rate of supratidal tidal delta accretion at the four Rhode Island inlets based on photogrammetric mapping for 1939-1975 period. Flood tidal delta deposits (supra and subtidal) are 1 1/3 times greater than total washover accretion along this coast (Fisher & Simpson, 1979).

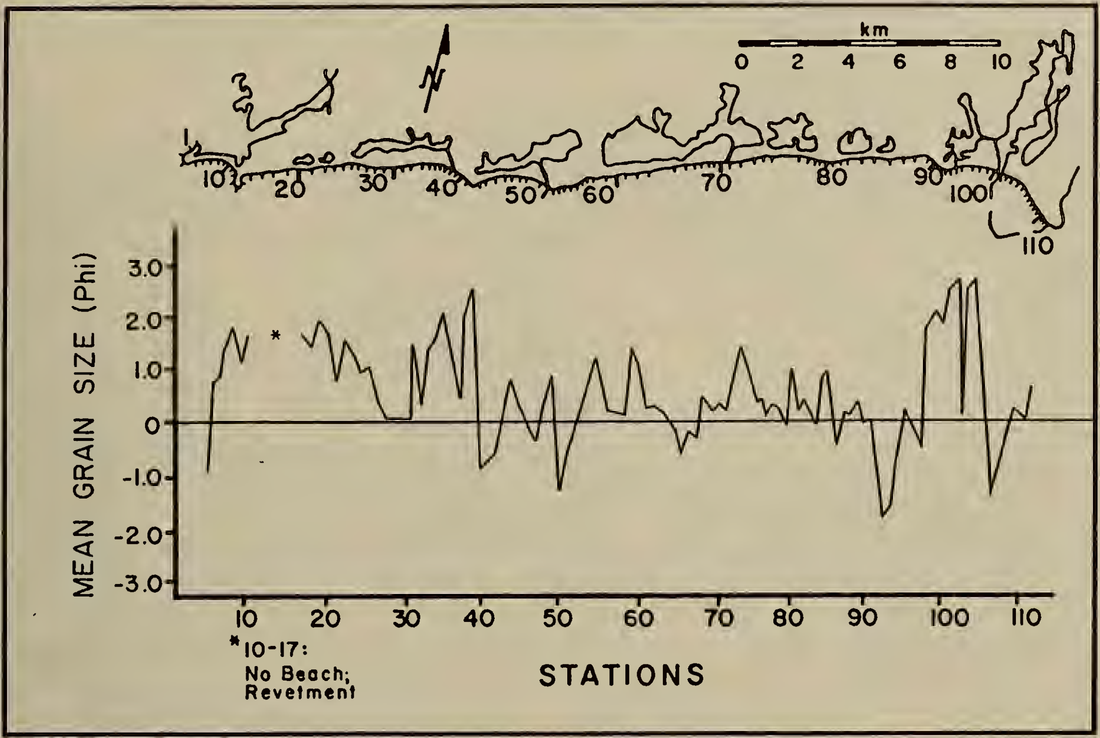


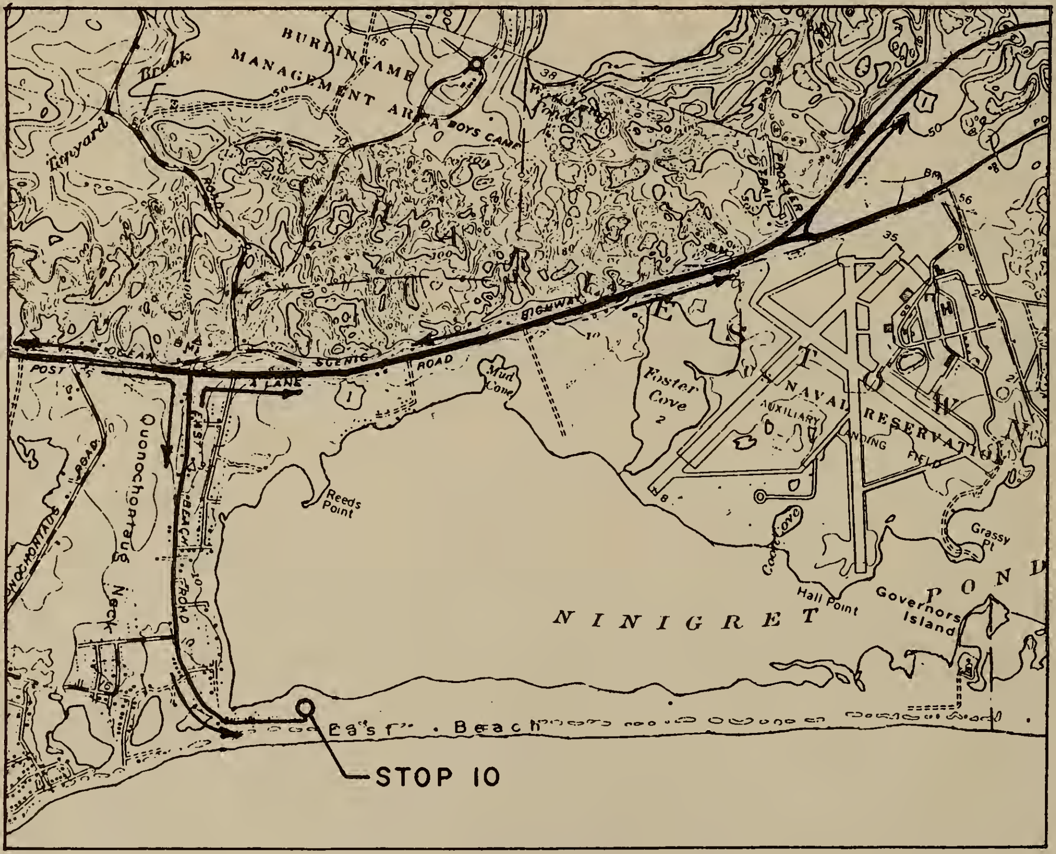
Figure 7. Mean grain size plot of foreshore sediments (Phi units) at 94 stations (excluding revetment stations) sampled August, 1977. The central portion of the shoreline exhibits a lack of the finer grain sizes (Fisher & Hagstrom, 1980).

32.5 Turn right leaving Fishing Area parking lot
33.1 Pull off road to right at Weekapaug Point, STOP 9

STOP 9. Weekapaug Point (Map 3) - Weekapaug Point is a mainland headland beach, not a barrier beach. The mainland is covered with a bouldery glacial till because of the crystalline rock from which the glacier derived this till. As wave action removes the sand and finer sediments, the large size material remains behind as a lag deposit. These deposits, up to boulder size, form the boulder shore platform seaward of the beach. On a standard embayed shoreline of submergence these headlands would be considered the source areas of the sediment of the downdrift (east) barrier beach. To test this model a series of regional sediment and profile sampling programs were carried out at 4 month intervals in August, 1977; March, 1977, and October, 1976 (Fisher & Hagstrom, 1980). Fall 1976 was a period of increased shore and dune erosion due to a hurricane striking this coast in August, 1976. Factoral analysis of sediment parameters indicate a three-part seasonal coastal pattern (Figure 7) with the eastern and western, but not central, sections showing: decreasing grain size, better sorting from winter to summer beaches, decreasing foreshore slope and increasing foreshore width. Where erosion rates (short and long-term) are above average, beach sediments are on the average also coarser. There was no consistent pattern of coarser sediment at headland beaches and finer sediment at the barrier beach. This three-part pattern is probably controlled by a combination of wave refraction by offshore Block Island, wave shadows at the Pt. Judith breakwater, and longshore drift disturbance at the jettied inlets.

33.1 Continue ahead along road
33.2 Bear right at intersection
33.4 Turn around at Weekapaug Fire District Beach parking lot
34.3 Retrace route to Weekapaug Breachway continuing straight ahead (Weekapaug Rd)
35.1 Turn right on US 1A North (Shore Rd.)
36.6 Bear right at intersection with US 1 (4-lane) to Narragansett & Wakefield
38.8 Turn right on East Beach Rd.
39.9 Turn left along beach
40.2 Park at Ninigret Conservation Area parking lot, STOP 10

STOP 10. East Beach (Map 4) - East Beach is the location of the Ninigret State Conservation Area. A large out-door display panel, erected by the R. I. Department of Environmental Management and the Audubon Society, describes the geology of the Ninigret barrier and has an aerial view of the barrier, the pond and the mainland. All cottages along East Beach were destroyed by the 1938 hurricane but homes built again were destroyed by the 1954 hurricane with damages of $358,000. When construction began again, the state condemned the barrier beach, some 3 miles to the Charlestown breachway, and manage it as a conservation area. A coastal management report pointed out that the low elevations of the poorly vegetated frontal



Map 4 - Stop 10, East Beach, Ninigret Conservation Area (Quanochontaug Quadrangle).

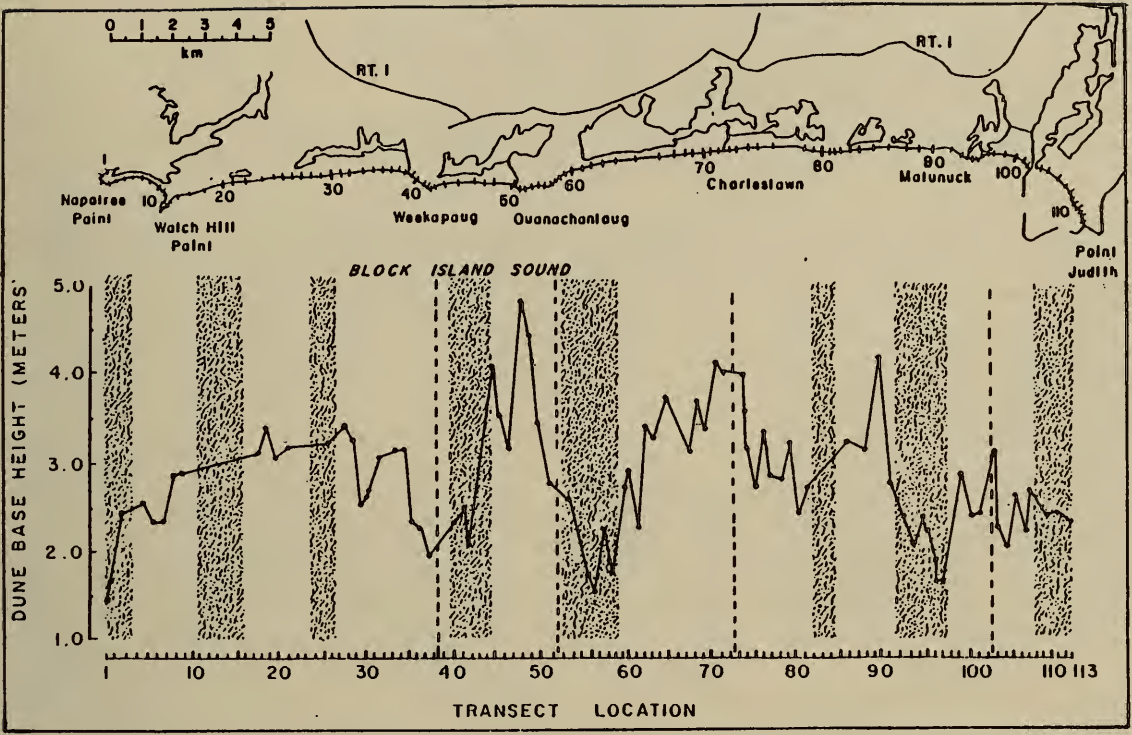


Figure 8. Plot of dune base elevation at 106 beach/dune profile stations for survey in October, 1976, indicates statistically a greater relationship to long term beach erosion trends than other profile parameters (Fisher & Gautie, 1978). Stipple at headlands, dash line at inlets.

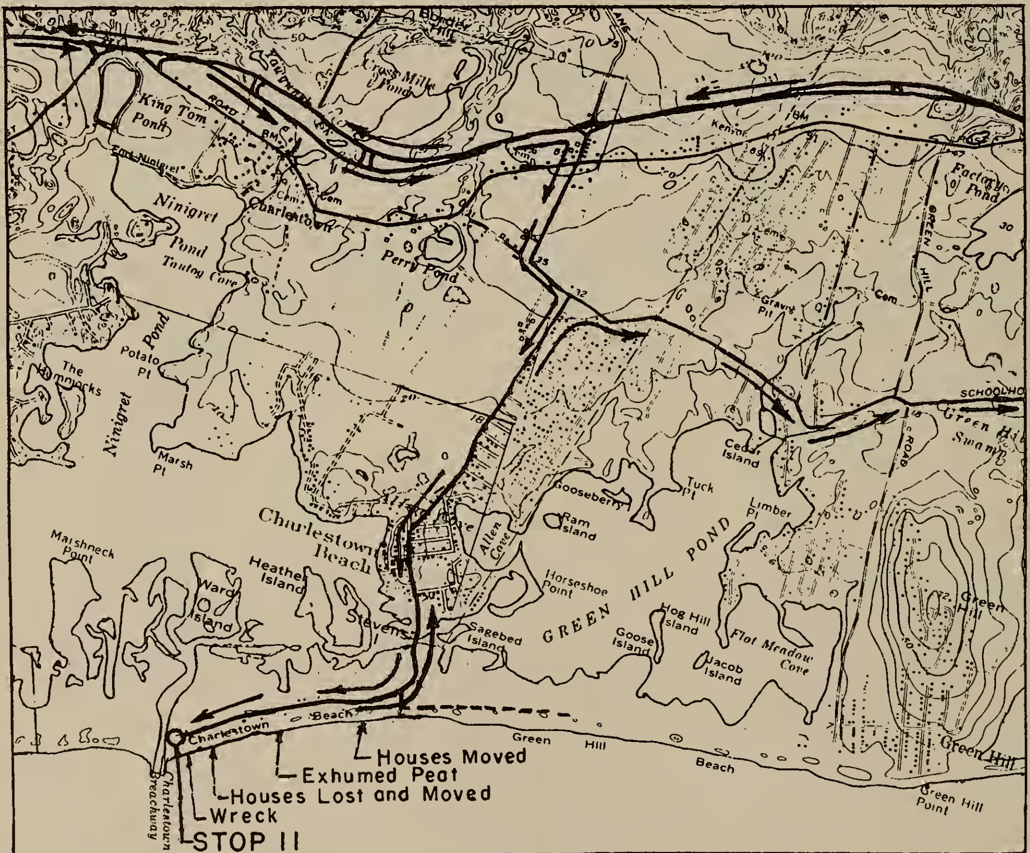
dune crest reduces the effectiveness of this barrier as a storm buffer for Ninigret Pond and the back pond residences. To determine the relationship of long-term erosion trends to beach and dune topography, 106 stations along the Rhode Island barrier coast were transect surveyed from dune crest to low tide level in Fall, 1976 (Fisher & Gautie, 1978). Factoral analysis was conducted of the following topographic parameters: foreshore slope, foreshore, backshore, and total beach width as well as the elevation of berm crest, frontal dune crest and frontal dune base. This statistical analysis determines which parameter is most responsible for differences between different beaches. Discriminate analysis indicated that dune base height (elevation), not dune crest height or beach width, was the most significant parameter for different beaches when related to long-term erosion rates of these same beaches (Figure 8). Therefore, prediction as to whether a beach is eroding more than the regional average can be determined to a first approximation, by determining whether its dune base height is lower or higher than the regional average of the same coastline.

In the mid-1970's, environmental impact studies were conducted in this area for a proposed nuclear power plant to be built on the mainland at an abandoned military airfield across Ninigret Pond. The intake and outfall pipes for reactor cooling were to extend beneath the pond and barrier and discharge offshore in 60 feet of water. In 1980 the EPA ruled that a federal conservation area was instead the best use of the airfield.

41.7 Return along East Beach Rd. to US 1 and turn right on US 1
47.9 Turn right on road to Charlestown Beach
48.0 Continue straight ahead at intersection with US 1A
48.2 Turn left at intersection (Beach/Breachway sign)
48.3 Turn right on Charlestown Beach Rd.
49.7 Continue on dirt road bearing right after Charlestown Beach parking lot
50.5 Enter Charlestown Breachway parking lot, STOP 11

STOP 11. Charlestown Beach (Map 5). This beach is highly developed with numerous summer homes of out-of-state owners. During the 1938 hurricane numerous homes were destroyed or floated across Ninigret Pond. The 1938 hurricane stillwater level was 16.5 feet above mean sea level. In order to qualify for low cost federal flood insurance, houses must have the first floor above the "standard flood project" height of 11.5 feet above mean sea level. Therefore, almost all homes along this beach are built on elevated pilings.

From the summer of 1976, and for a period of two years, this beach experienced the most severe beach erosion along the Rhode Island coast for the last 20 years. Several homes on the front dune were lost to the sea along this beach. The most interesting aspect was that this erosion did not occur during a hurricane or even during "northeaster" storms. Both the beach and dune erosion continued for a period of years. Some of the reasons suggested for the initiation of this erosion were: changes in the prevailing wind patterns, changes in storm intensity, changes in storm tracks or the after



Map 5 - Stop 11, Charlestown Beach (Quonochontaug Quadrangle).

effects of a minor hurricane that struck August, 1976, but caused no damage.

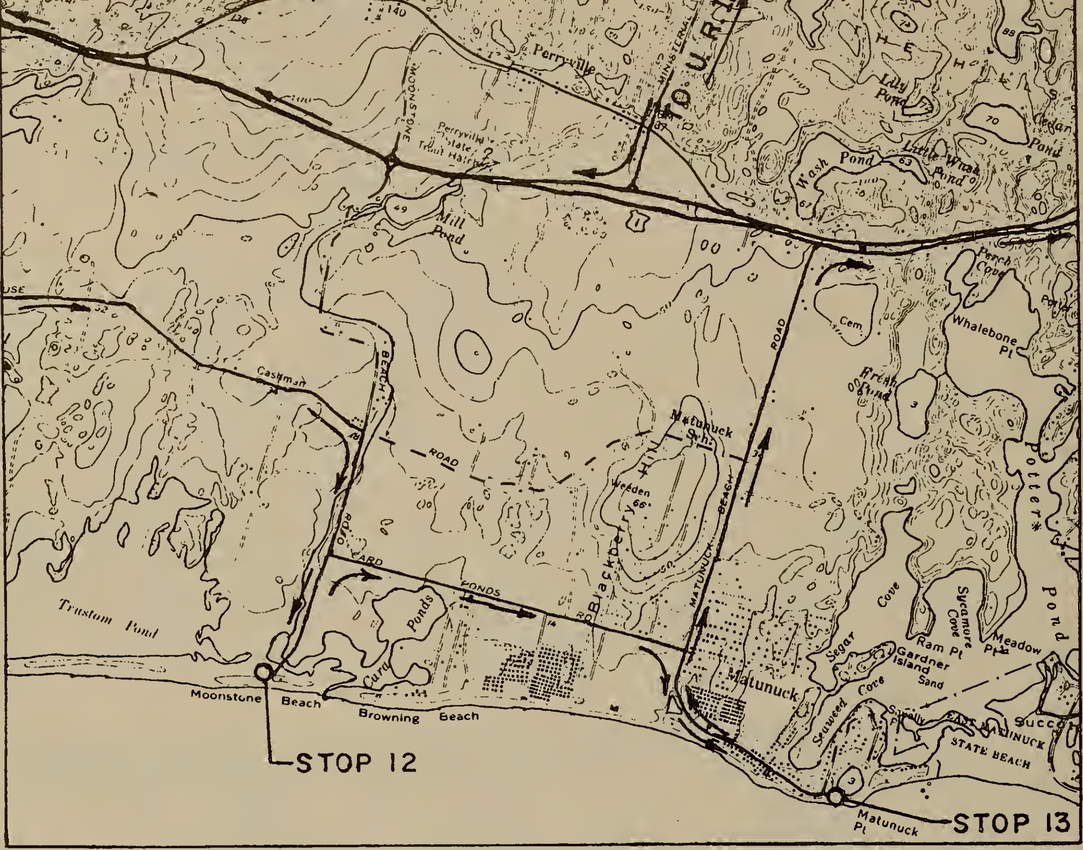
The effects of this erosion can be reconstructed in a beach walk from the Charlestown Breachway, 0.5 mile east, to the Charlestown Beach right-of-way and by reference to photographs taken during the erosion (Pl. 2-5). At the inlet, sediment deposition is usually equal along both jetties, however in 1976-77 excessive accumulation occurred on the west side, while the beach and dune on the east side eroded (Pl. 2). During this time, further down the beach, just opposite the parking lot, the erosion was so great that a shipwreck buried under the beach and dune was exposed (Pl. 3). Rebuilding of the beach by natural processes has again covered this hull with beach sand. While beach erosion was great, it was actually dune erosion that caused the loss of the house. The support pilings were not driven deep enough into the dune and as the dune face eroded, the complete pilings were exposed and the houses collapsed seaward (Pl. 4). Finally half-way along the beach, during spring low tide, in March, 1977, an extensive peat layer was exposed on the lower foreshore. This peat was identified as tidal marsh peat and was carbon-dated by the author at 600 B. P. This date means that 600 years ago this peat was deposited in a lagoon behind a barrier beach, a barrier beach that had to be a minimum of 500 feet offshore. What is now the barrier beach was a tidal pond. This documented migration of the barrier beach landward by overwash is what preserves the barrier beach in the face of a rising sea level. Rather than drowning, it "rolls-over" itself (Dillion, 1970) and so preserves itself.

50.5 Return along Charlestown Beach Rd.
52.6 At end of road turn <u>right</u> on Matunuck School Rd.
53.9 Continue on Matunuck School Rd. bearing <u>right</u> and then <u>left</u> at Green Hill Beach Rd. intersection
55.5 Turn <u>right</u> on Moonstone Beach Rd.
55.9 Continue straight ahead on dirt road (Moonstone Beach entrance)
56.3 Park on <u>left</u> in Moonstone Beach parking lot, <u>STOP 12</u>

<u>STOP 12</u>. Moonstone Beach (Map 6) - This undeveloped beach, leased by the town of South Kingstown, is part of the Audubon Society wildlife refuge 600 feet to the west and a federal wildlife refuge further to the west. During the severe dune erosion period of 1976-78, two discoid pebble layers, together with an organic zone, were mapped in the dune face at 6.5 feet and 8.0 feet above the high tide line. They are tentatively considered to be lag deposits from washovers of the 1938 and 1954 hurricanes. Dune accretion above these layers suggests a rate of one inch per year of vertical dune growth. Further west, a former inlet site can be recognized from relict flood tidal delta marshes in Trustom Pond. The term "moonstone" refers to the numerous discoid shaped translucent white vein quartz pebbles common on the lower foreshore. Card Pond to the east often has a temporary high water inlet through the beach.

56.3 Return along dirt road to entrance
56.8 Turn <u>right</u> at intersection on Card Pond Rd.
57.8 Turn <u>right</u> at intersection, Town of Matunuck, and follow road along beach
58.6 Turn <u>right</u> into Deep Hole Fishing Area parking lot, <u>STOP 13</u>

<u>STOP 13</u>. Matunuck Point (Map 6) - Matunuck Point is a headland beach developed from a glacial till headland. Wave erosion of this deposit has left a lag deposit as a boulder pavement extending 300 feet offshore at low tide.



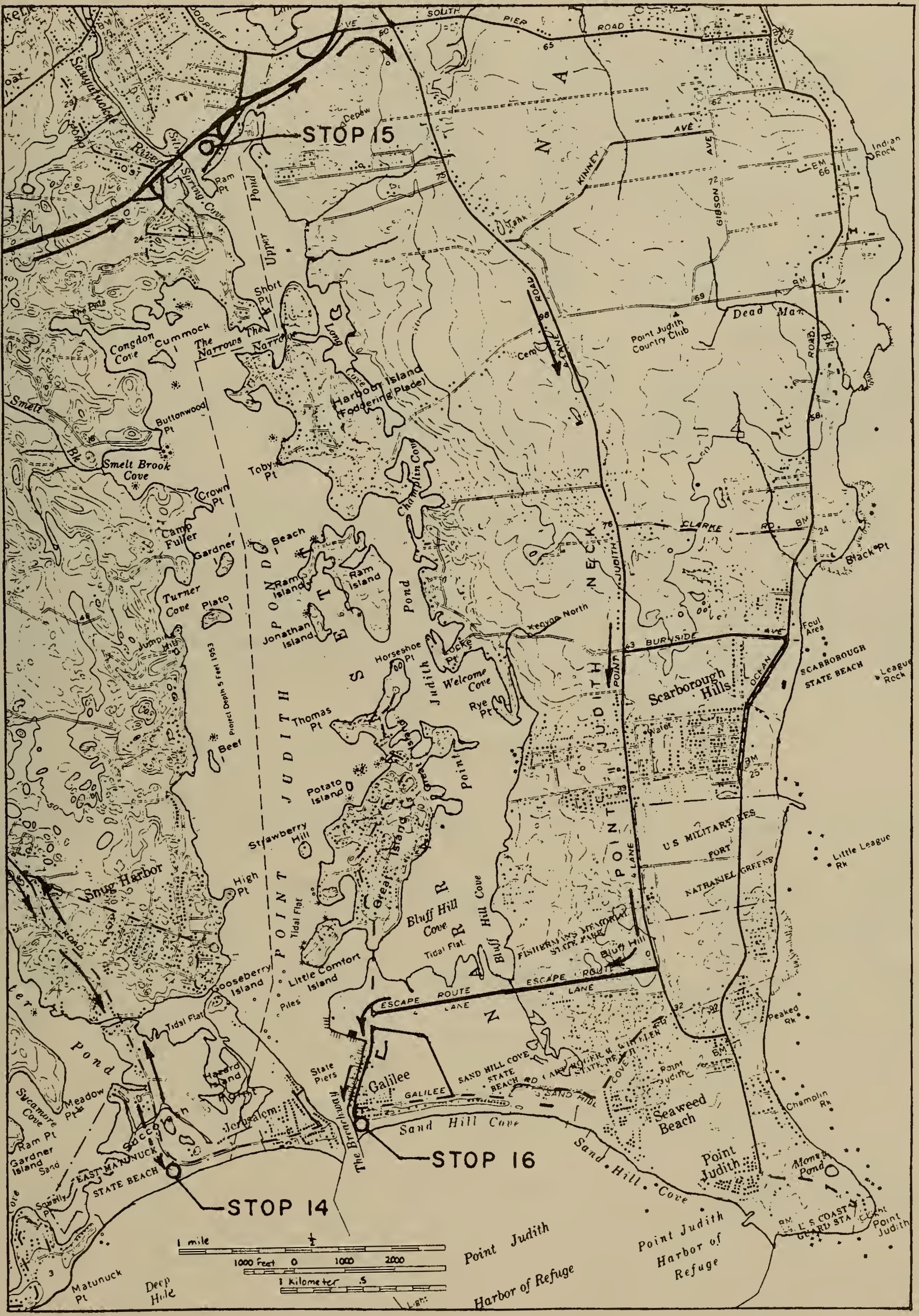
Map 6 - Stop 12, Moonstone Beach; Stop 13, Matunuck Point, Deep Hole Fishing Area (Kingston Quadrangle).

Wave refraction around this boulder pavement provides good surfing waves. Deep Hole refers to a popular offshore fishing hole that is probably related to the glacial topography on land and may be a drowned kettle hole.

58.6 Return along Ocean Rd. and continue straight ahead on Matunuck Beach Rd.
60.7 Turn right at intersection with US 1
61.5 Turn right to State Beach, East Matunuck (sign), on Succotash Rd.
63.3 Park at State Beach parking lot on right, STOP 14

STOP 14. East Matunuck State Beach (Map 7) - The parking lot and bathhouse of this state beach are located directly over the old inlet into Point Judith Pond and much of the tidal marshes to the north are the vegetated relict flood tidal delta deposits. Preservation of these salt marshes from parking lot encroachment during development of this beach in the mid-1970's led to numerous state and conservation group discussions. Problems with beach grass not growing on artificial dunes, heated summer parking lot runoff into the marshes and beach sand overwash into the marsh were some of the possible problems.

63.3 Leave State Beach and return to US 1 on Succotash Rd.



Map 7 - Stop 14, East Matunuck State Beach; Stop 15, Pt. Judith Pond; Stop 16, Galilee (Kingston and Narragansett Pier Quadrangles).

65.1 Turn right on US 1
68.5 Just after 2 bridges turn right at Marina Park exit and park right in South Kingstown Heritage Park parking lot, STOP 15

STOP 15. Point Judith Pond (Map 7) - Marina Park (Heritage Park) overlooks the head of Pt. Judith or "Salt Pond" which extends over 3.5 miles to the ocean. Where as all the other coastal ponds are elongated parallel to the coast, only Point Judith Pond is elongated perpendicular to the coast. The other ponds developed from glacial meltwater channels, while Point Judith Pond developed from a pre-glacial buried river valley. It could be considered a "drowned river valley" as is Narragansett Bay to the east.

68.5 Leave parking lot and return to highway turning right on US 1 north.
69.0 Exit right to US 1A, Rt. 108 and Point Judith (signs)
69.4 Turn right at stoplight on Rt. 108 south (Point Judith Rd.)
73.1 Turn right to Galilee just beyond Fishermens Memorial State Park
74.2 Turn left at intersection (road now one-way)
74.6 Park on right at Galilee Breachway state parking lot, STOP 16

STOP 16. Galilee (Map 7) - The Breachway at Galilee is an artificial inlet that was cut open when the natural inlet to the west shoaled closed. Extensive jetties and dredging maintain this channel for the fishing fleet and the Block Island ferry. Sand Hill Cove beach to the east of Galilee is the easternmost barrier beach along the Rhode Island south shore. It has a well developed frontal dune and extensive tidal marshes behind it, probably relict flood tidal deposits from an earlier inlet which migrated eastward up against the Point Judith headland ridge.

Summary

A regional inventory of the coastal geomorphology and sediments of the entire Rhode Island south shore barrier beach shoreline was conducted on a long-term and short-term basis to provide a data base for coastal management purpose as follows:

I. Photogrammetric mapping of the 1935-1975 period revealed the following long-term changes:

A. The entire coast is eroding and the average rate is 0.2 m/yr. The only long-term accretion was on the up-drift side of inlet jetties.

B. Frontal barrier dunes along this coast are also eroding and the rate and pattern is similar to the above shoreline erosion.

C. Flood tidal delta deposition at the 4 south shore inlets is 1 1/3 times greater than accretion by washovers along the entire coast.

D. Washovers occur more on the western half of the coast. Where washover deposition is above average, beach erosion is above average 27% of the time.

II. Short-term seasonal synoptic regional inventory surveys and sampling revealed the following:

A. Regional beach and dune profile surveys indicate that it is the elevation of the base of the dune that is the best indicator of long-term erosion trends.

B. Regional seasonal beach sediment sampling, at a 4 month interval, indicates a three part pattern for the coast with coarser grain sizes in the center. Where long-term erosion rates are above average, beach sediments are also coarser.

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NOTES

THE GEOLOGIC SETTING OF COAL AND CARBONACEOUS MATERIAL, NARRAGANSETT BASIN, SOUTHEASTERN NEW ENGLAND

D.P. Murray[1], J.D. Raben[2], *P.C. Lyons[3], and H.B. Chase, Jr.B.[4]

[1]Dept. of Geology, Boston Unversity, Boston, MA 02215
[2]New England Geotechnical Consultants, Inc., 83 Codman Hill Ave., Dorchester, Ma
[3]U.S. Geological Survey, 956 National Center, Reston, VA 22092
[4]Consultant, 18 Beech St., Mansfield, MA

INTRODUCTION

The Narragansett Basin (Fig. 1) is a 1600 km^2 structural and topographic depression in southeastern Massachusetts and Rhode Island in which Pennsylvanian coal-bearing sediments have been variably metamorphosed and deformed, and intruded by the Permian-aged Narragansett Pier Granite. It supported intermittent and limited coal mining during the nineteenth and, to a lesser extent, twentieth century. The most successful mines were at Portsmouth (Stops 2 & 3) and Cranston (near Stop 5) Rhode Island, although current activity is limited to the Masslite Quarry area (Stop 4).

It is of interest for several reasons. First, the Narragansett Basin is a particularly appropriate place to study the response of organic material to progressive metamorphism, as through outcrop and drillcore one can sample carbonaceous material and associated sediments from sub-greenschist to upper amphibolite facies conditions, a situation rarely found in other metamorphic terranes. The topic has received surprisingly little attention, given: 1) the importance of this type of metamorphism in terms of the global recycling of carbon; 2) the control organic material exerts upon the chemical environment during metamorphism; and 3) the fact that coal cannot retrograde metamorphose, making it an ideal candidate to "remember" peak metamorphic conditions in polymetamorphic terranes. Second, it contains the most complete record of the Alleghanian orogeny, an event that represents a major episode of deformation, regional metamorphism, and plutonism that was the consequence of the final (and perhaps most important) stage in the evolution of the Appalachian orogen (described more fully in Mosher and others, this volume). Finally, with the possible exception of peat deposits, the coal deposits represent the only indigenous fossil fuel energy resource in New England, and as such merit consideration.

The purpose of this trip is to examine the field relationships of the major deposits of coal and carbonaceous materials in the basin, that occur over a range of metamorphic and deformational conditions. Part of the trip will also consist of examination of mesoscopic and microscopic features of the coal and associated rock, as seen in drillcore and under the microscope.

Much of the organic material in the Narragansett Basin does not qualify as coal in the strict sense, because either the rank is too high and/or the ash content is too great. We will use the term coal, however, to refer to all of the material, with additional description as appropriate.

* "The paleobotany section was written by P.C. Lyons".

Figure 1. Geologic map of the Narragansett basin. Modified from Murray and Skehan, 1979.

GEOLOGIC SETTING

The non-marine clastic sediments of the basin rest at least in part unconformably upon an Avalonian (Rast and Skehan, this volume; Dreier and Mosher, this volume) terrane comprised primarily of Late Precambrian to Cambrian sediments, volcanics, and volcaniclastics. Although the basin/basement contact of the basin is largely unexposed, it appears to be mainly (entirely ?) faulted along its western margin, and for the other margins at least locally unconformable upon the basement. Several horsts of granitic basement occur within the basin, and recent offshore geophysics suggest that the Narragansett Basin plus several of these horst blocks extend at least 33 kilometers southward under Long Island Sound (McMaster and others, 1980). Gravity traverses across the basin (Appendix E in Skehan and Murray, eds., 1978) indicate an irregular surface, probably developed on faults, that in places is at least 3,000 meters deep. More detailed discussions of the geology are given in Quinn (1971), Quinn and Moore, (1968), Skehan and Murray (1980), and Murray and Skehan (1979).

Five formations, now referred to collectively as the Rhode Island Bay "Group" (Skehan and others, 1979) are recognized, and their stratigraphic relationships are shown in Figure 2. Of these, the Rhode Island Formation is by far the thickest (>3000m), contains all of the coal measures, and has an extensive and well documented megaflora (Lyons and Darrah, 1978). It consists (in order of decreasing abundance as seen in drillcore) of sandstone, siltstone, conglomerate, shale, and coal. The abundance of coarse grained material, together with a variety of primary sedimentary features (redbeds, recognizable channels, festoon cross bedding, absence of any limestones, etc.) indicate a non-marine, clastic origin for the entire "Group". The preferred depositional environment is that of humid alluvial fans and meandering streams in an intermontane basin, where coal swamps formed either along flood plains parallel to channels or behind alluvial fans. Deposition was probably rapid and at least locally synorogenic. The stratigraphic section may also have been relatively both younger and thinner in the southern Narragansett Basin. Additional information concerning the stratigraphic relationships and their interpretation may be found in Towe (1959), Mutch (1968), Skehan and others (1979), and Severson and Boothroyd (1981).

The northern half of the Narragansett Basin was slightly metamorphosed (anchizone, see Hepburn and Rehmer, this volume) and deformed into open, upright east-northeast trending, northwest verging folds). In contrast, the southern portion underwent multiple episodes of folding and faulting accompanied by a Barrovian metamorphism (see Burks and others, this volume). The earliest, most intense, and most widespread episode (D1) is characterized by northwest verging folds and thrusts that are synchronous to slightly older than the regional metamorphism. The next episode (D2) of folding was roughly coaxial, with westward dipping axial planes, and usually of a smaller scale relative to the first episode. A third episode of folding (D3) is about roughly east-west axes, and may be correlative with the single folding event in the northern half of the basin. A second, retrograde metamorphism was syn- to post-D3. The intensity as well as complexity of the structure of the southern part of the Narragansett Basin is greatest along the trace of the Beaverhead fault, and Stop 2 may be within this fault zone. The Narragansett Pier Granite intrudes the southwestern margin of the basin, and at least locally truncates the Barrovian facies series isograds. The granite is post-D2 fabric, although whether it post-dates all of the deformation and metamorphism is unclear. The age of the granite is precisely bracketed, as it contains Late Pennsylvanian plant fossils

TIME-STRATIGRAPHIC UNITS: EPOCH, NORTH AMERICA	TIME-STRATIGRAPHIC UNITS: STAGE, EUROPE	FLORAL ZONES OF READ AND MAMAY (1964)	ROCK-STRATIGRAPHIC UNIT, CENTRAL APPALACHIANS: CENTRAL AND WESTERN PENNSYLVANIA	ROCK-STRATIGRAPHIC UNIT, CENTRAL APPALACHIANS: EASTERN PENNSYLVANIA		ROCK-STRATIGRAPHIC UNIT, CENTRAL APPALACHIANS: WEST VIRGINIA	ROCK-STRATIGRAPHIC UNIT, NEW ENGLAND: MASSACHUSETTS RHODE ISLAND	NEW ENGLAND: FLORAL LOCALITY	NEW ENGLAND: LOCALITY NUMBER	NEW ENGLAND: REFERENCE
LATE PENNSYLVANIAN	Stephanian B or C	11 or 12	Waynesburg Fm. (lower part)	No rocks at surface		Waynesburg Fm. (lower part)	Dighton Conglomerate			This report
			Monongahela Group			Monongahela Fm.	Rhode Island Formation (upper part)	Pawtucket, RI	10	Lesquereux (1889)
	Stephanian A or B	11	Conemaugh Group (upper part)	Llewellyn Formation		Conemaugh Formation (upper part)		Portsmouth, RI Seekonk, MA Easton, MA	42 14 70	Darrah (1969) Lyons and Darrah (1978)
	Cantabrian Westphalian D (upper)	10	Conemaugh Group (lower part)			Conemaugh Formation (lower part)	Rhode Island Formation (middle part)	Plainville, MA	54	Hitchcock (1861)
MIDDLE PENNSYLVANIAN	Westphalian C (upper) and D (lower)	10	Allegheny Group (upper part)			Charleston Sandstone of Campbell and Mendenhall (1896)	Rhode Island Formation (lower part)	Foxboro, MA	24	Lyons (1969)
								Mansfield, MA	16	Lyons and Chase (1976)
	Westphalian C (late)							Worcester "coal mine", MA	—	Grew and others (1970)
	Westphalian C (early)	9	Allegheny Group (lower part)					Plainville, MA	20	Oleksyhyn (1976)
								Valley Falls, RI	1	—Round (1920)
		7,8	No rocks at surface	Sharp Mountain Member	Pottsville Formation	Kanawha Formation	Wamsutta Formation (upper part)	Attleboro, MA	56	Knox (1944)
EARLY PENNSYLVANIAN	Westphalian B or C	6		Schuylkill Member		New River Formation	Wamsutta Formation (lower part)	None	—	—
	Westphalian A and B	5					Pondville Conglomerate (upper member)	Canton, MA	139	Lyons and others (1976)
	Namurian C Namurian B	4		Tumbling Run Member		Pocahontas Formation	Pondville Conglomerate (lower member)	None	—	Skehan, Murray, Hepburn, and others (1979)

Figure 2. Stratigraphic relationships in the Narragansett basin. Modified from Lyons (1981, in press). Locality numbers refer to Fig. 2 (Lyons, 1981, in press).

within pendents (Brown and others, 1978), and primary monazites that give a U/Pb age of 275 m.y. (Kocis and others, 1978). (The locale from which these radiometric and floral dates were obtained is a stop in both the Burks and others and Hermes and others trips in this volume.) The granite undergoes a variety of changes along its contact with the carbonaceous metasediments (color change, variations in mineral assemblage) that are probably the consequence of the interaction of contrasting fluid phases associated with the relatively oxidized granite and relatively reduced metasediments, respectively (Murray and Skehan, 1979).

Mineral assemblages (Grew and Day, 1972) and chemistry (Murray, unpub. data) imply peak metamorphic conditions of $T=600^{\circ}C$ & $P=5-6$ kbar for the southern part of the basin (Fig. 4). Based upon coal petrology (Gray and others, 1978; Raben and Gray, 1979; Murray and Raben, 1980) and illite crystallinity (Rehmer and others, 1978; Rehmer and Hepburn, this volume), temperatures of the order of $200+^{\circ}C$ are believed to have been attained in the northern part of the basin. The distribution of isograds is given in Figure 2 of Burks and others (this volume) and in Murray and Raben (1980).

The Narragansett Basin is unusual in that it contains not only radiometric (Rb/Sr, U/Pb, K/Ar, and incremental argon) but also abundant megafloral dates in rocks from a wide range of metamorphic conditions, and this permits a precise definition of the duration of the Alleghanian orogeny in southern New England. The preferred interpretation consists of the following stages: 1. Rapid, synorogenic deposition of non-marine clastic sediments from Westphalian A (or older ?) times (310 m.y.) through Stephanian B or younger (≤ 285 m.y.); with the stratigraphic section in the southern Narragansett Bay area possibly thinner and younger than that of the rest of the basin. 2. Several composite episodes of ductile and brittle deformation accompanied by regional metamorphism followed; emplacement of S-type Narragansett Pier granite occurred towards the end of this orogenic cycle. 3.Preliminary incremental argon ages (Dallmeyer, 1981) imply fairly rapid uplift. These events represent, essentially, a continuum that suggests that the Alleghanian orogeny was a relatively abrupt though intense event in southern New England.

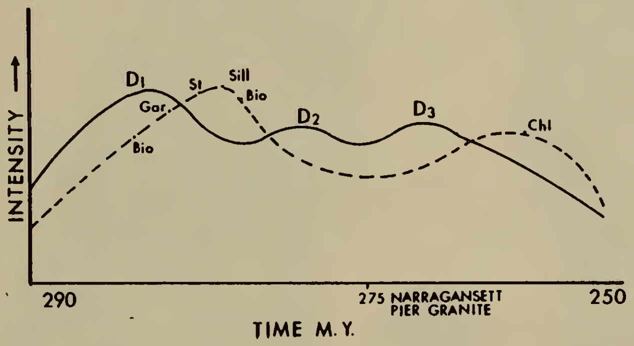


Figure 3. Variation of intensity of metamorphism and deformation with time, in the southern Narragansett Basin.

PALEOBOTANY

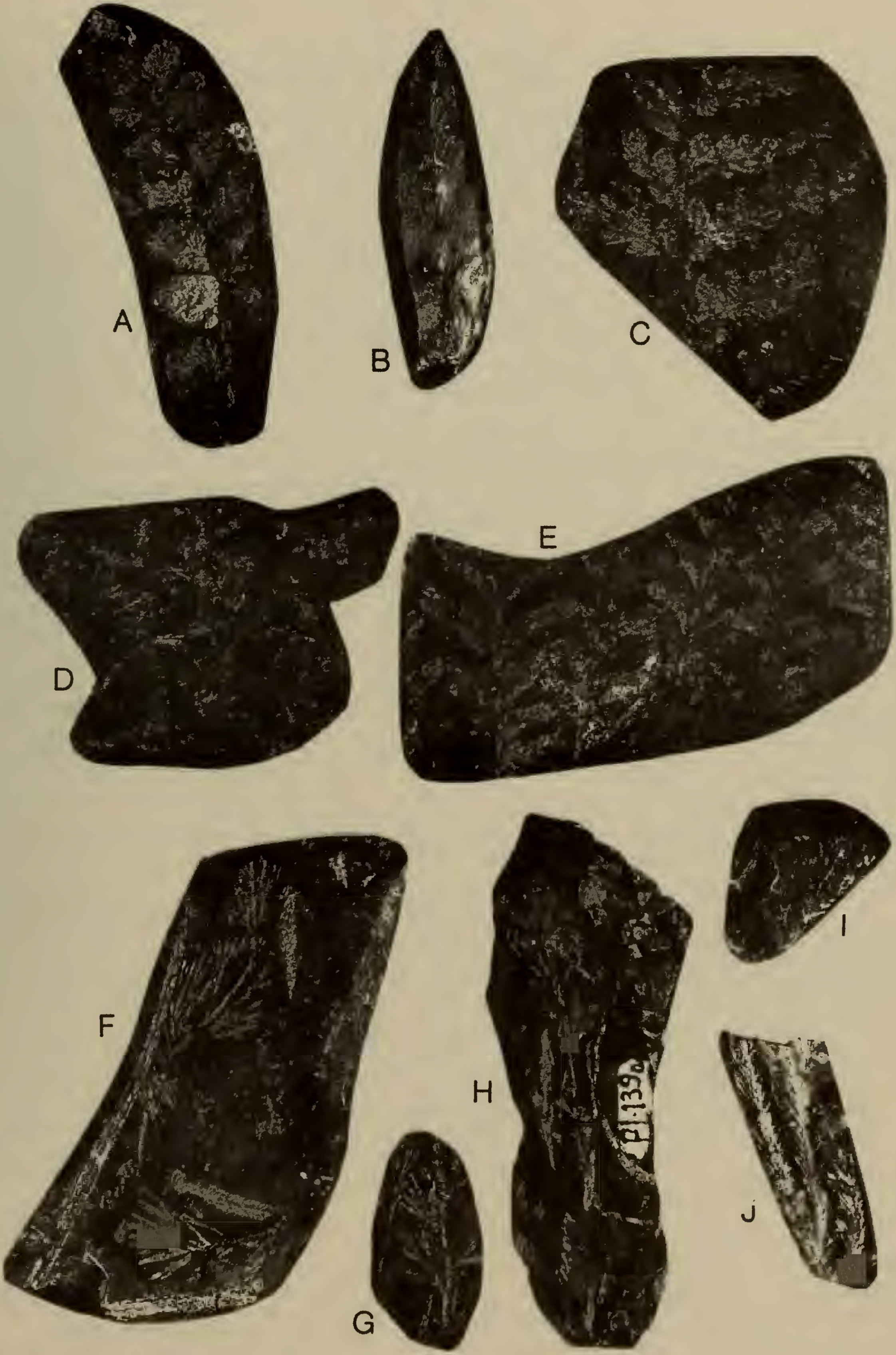
The Narragansett basin has a rich megaflora consisting of roughly 300 nominal species, nearly all of which are from the Rhode Island Formation, and a much smaller fauna dominated by cockroaches. The biostratigraphy has been described in a series of recent articles by P. Lyons and colleagues (listed in References Cited), and will not be repeated here. Rather, a summary of the biostratigraphy of the richest floral locale, the Masslite quarry (Stop 4), will be presented. This locale represents one of the oldest sections of the Rhode Island Formation yet identified. Continuous core drilling has shown that the section is approximately 300 meters above basement. The contact is an angular unconformity, which is directly overlain by 20 meters of arkosic conglomerate.

Paleobotany of Masslite Beds

Plant fossils have been used extensively to date and correlate the coal-bearing rocks of the Narragansett basin. These rocks range in age from Middle to Late Pennsylvanian, corresponding to Westphalian C to Stephanian B of Europe (Fig. 2). The coal beds of the Masslite quarry (Lyons and Chase, 1976) contain the oldest known beds in the Narragansett basin and have been dated as Westphalian C (Oleksyshyn, 1976). A summary of species found in the Masslite (and surrounding areas) flora is given in Lyons and Chase (1976, Table 1).

The earliest illustrations of plant fossils from the Masslite quarry (Lyons, 1969) are of *Annularia sphenophylloides*; *Alethopteris serlii*; *Eremopteris* species (Lyons, 1969, Pl. VIII, Fig. A), which may be *Eusphenopteris* cf. *neuropteroides* Van Ameron; and a *Sphenopteris* species (Lyons, 1969, Pl.XV, Fig. B), which is similar to *Mariopteris* cf. *paddocki* (Oleksyshyn, 1976, Fig. 11C). The most detailed description of fossils in the Masslite quarry is found in Oleksyshyn (1976), who illustrated and described 28 species including 10 sphenopsids; 2 new species, *Palmatopteris narragansettensis* and *Palmatopteris plainvillensis*; and 3 pecopterids referred to as *Pecopteris clarkii*, *P. miltoni*, and *P. hemitelioides*. Other illustrations of plant fossils constituting flora of the Masslite quarry can be found in Lyons and Chase (1976), Lyons and Darrah (1979), and Lyons (in press). Eight species of plant megafossils found at the Masslite quarry are illustrated in Figure 4. Newly illustrated species are *Pecopteris* cf. *dentata* (Fig. 4C), *Pecopteris* cf. *plumosa* (Fig. 4E), and a *Crossotheca* species (Fig. 4D). Two important species not reported by Oleksyshyn (1976) and found by Lyons at the Masslite quarry are *Sphenophyllum cuneifolium* and *Neuropteris scheuchzeri* (Fig. 4B).

Figure 4. A, *Neuropteris* cf. *loshi* Brongniart, Pl-6, HU-45759; B, *Neuropteris scheuchzeri* Hoffmann, Pl-33, HU-45753; C, *Pecopteris* cf. *dentata* (Brongniart), Pl-135, HU-45760; D, *Crossotheca* sp., Pl-6, HU-45759; E, *Pecopteris* cf. *plumosa* Artis, Pl-35, HU-45760; F, *Eremopteris lincolniana* D. White, *Sphenophyllum emarginatum* Brongnart, Pl-139a, HU-45762; I, *Sphenophyllum emarginatum* Brongnart, Pl-139a, HU-45762; J, *Lepidodendron* cf. *lanceolatum*, Pl-36, HU-45750; Pl- original field number; HU- Harvard University Paleobotanical Collections Specimen Number; Scales for figures: B, 1.4X; H, 1X; J, 0.65X; all others 3X.


A
B
C
D
E
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P1.139a
I
J

Age and Regional Correlations of the Masslite Beds

Oleksyshyn (1976) referred the Masslite flora to Westphalian C, an age which is in agreement with that for the Foxboro beds (Lyons, 1969, 1971). Recent work in the proposed Pennsylvanian Stratotype of West Virginia and Virginia (Englund and others, 1979) allow correlations on the basis of the megaflora. The presence of *Alethopteris serlii*, *Neuropteris scheuchzeri*, *Annularia sphenophylloides*, *Sphenophyllum cuneifolium*, and *Sphenophyllum emarginatum* at the Masslite quarry indicates a correlation with the upper part of the Kanawha Formation and Charleston Sandstone; both Middle Pennsylvanian of West Virginia. The absence of *Neuropteris ovata* and the presence of *Sphenophyllum cuneifolium* in the Masslite flora are most indicative of the equivalent to the upper part of the Kanawha Formation, an interval above the Winifrede coal bed (Gillespie and Pfefferkorn, 1979).

The Masslite flora is close in age to the Foxboro beds, which were correlated by Lyons (1969,1971) with the lower part of the Allegheny Formation and assigned an age of Westphalian C. However, the Foxboro flora is probably somewhat younger, as evidenced by the presence of *Neuropteris ovata* (Lyons, 1969, Pl.IX, Fig. A), which is absent from the Masslite flora. The flora of the Hardon Mine at Mansfield is interpreted to be somewhat younger than the Foxboro flora because of the presence of the larger pinnuled form of *Neuropteris scheuchzeri* (Lyons and Chase, 1976, Fig. 4C), which is found in Westphalian D equivalents (Lyons, in press). In western Pennsylvania, the Masslite flora correlates closely with the flora of the Clarion coal bed near the base of the Allegheny Formation (Darrah, 1969). This correlation is mostly indicated by the lack of pecopterids, such as *Pecopteris lamuriana*, *P. unita*, and *P. candolleana*, which are found in the Middle Kittanning coal bed but not in the underlying Clarion coal bed (Darrah, 1969).

In Maritime Canada, the Masslite flora correlates most closely with the Minto flora of Westphalian C Age in the Pictou Group of New Brunswick (Bell, 1962), which was correlated by Lyons (1971) with the Foxboro flora. However, it appears that the Minto flora may be slightly younger than the Masslite flora as indicated by the variety of neuropterids in the Minto flora. The Masslite flora is probably transitional between the *Lonchopteris* zone (Westphalian B) and the *Linopteris obliqua* zone (Westphalian C) of the Morien Series of the Sydney coalfield of Nova Scotia (Bell, 1938). Thus, the age of the Masslite flora could be as old as late Westphalian B but not younger than early Westphalian C in Maritime Canada. Moreover, the northwest corner of the basin contains the oldest ages for the Rhode Island Formation yet recognized in the Narragansett basin, with slightly younger ages (Westphalian C) in the nearby Foxboro and Mansfield beds, and significantly younger beds (Stephanian A/B) occurring further to the east (Easton) and south (Portsmouth, Newport, and surrounding areas).

Plainville, Seekonk, Taunton, and Worcester. There were about 23 Rhode Island mines and prospects, in Bristol, Cranston, Cumberland, East Providence, Jamestown, Little Compton, Newport, Portsmouth, Providence, South Kingstown, and Warwick. It should be noted that many of these Rhode Island sites were actually "graphite" mines, and lie within biotite or higher metamorphic zones, where the term "graphite" refers to carbonaceous material partly to completely recrystallized and well ordered.

Some of these mines were open cuts, although most were vertical or slope shafts ranging in depth from a few dozen feet to the 2,100 foot Portsmouth incline. The coal was used for heating and cooking; in stationary engines and locomotives; for making lime, glass, and bricks; and in forges, bake ovens, and greenhouses. In 11 of the mines the coal was so thermally altered it could be used not only for fuel, but also as natural carbon. If sold for fuel it was locally called "coal"; if for foundry facings or paint it was called "graphite".

Between 1860 and 1883 Portsmouth anthracite was used successfully for smelting imported copper ore. From 1940 to 1959 Cranston coal was sold widely as amorphous graphite. At the Masslite quarry in Plainville, at least since 1967, indigenous coal and carbonaceous shale have been mixed with Pennsylvania coal (and since 1979 with fuel oil) and used as a heat source in the manufacture of lightweight aggregate. In all, about 1.36 million tons of coal have been mined in the Narragansett Basin. At the Portsmouth mine (1808-1913) at least 1.06 million tons were removed. Mining was conducted down a 31° dip, 4,600 feet along strike. At the Cranston mine (1857-1959) about 180,000 tons were taken from an open pit plus a slope 450 feet deep on a 19° dip, 1,270 feet along strike. At Mansfield, about 7,000 tons were mined prior to 1923.

Many other mines and prospects were opened in the Narragansett Basin , but none were as profitable. The mines failed mainly because the cost of pumping water and of working the irregular coal lenses required the inferior coal, usually poorly cleaned and prepared, to be sold at prices too near those of competing coals, which gave more heat and were less troublesome to use.

Narragansett Basin Exploration Project (1976-1980)

In response to the energy embargo of 1974, renewed interest was generated in the possible coal resources of New England. The result was an exploration program, managed by Weston Observatory (of Boston College), that relied heavily upon continuous core drilling. The program lasted from 1976 to 1980, and was funded primarily by NSF (RANN), U.S. Bureau of Mines, and finally D.O.E. During this time approximately 10,000 meters of NX drillcore were obtained, along with related field and analytical studies. Because of the lack of outcrop and inaccessibility of mines, this core represents the best source of data on the coals--it is currently stored at Weston Observatory, and is available for research. Although drilling took place throughout the basin, the emphasis was upon Plainville (Stop 4), Mansfield, Bristol, Somerset (Brayton Point), and Portsmouth (Stop 2). At present, there are no firm plans to continue exploration or to resume mining in the area. The results of this five year exploration project are contained in a series of reports (Skehan and Gill, 1981--this contains references to earlier reports), which may be obtained from Weston Observatory.

COAL AND GRAPHITE

Analytical Technique

Of the approximately 42 reported coal and graphite occurrences (25 mines & 17 prospects), we have chosen five locales for discussion that may be considered representative of the coal deposits found in the basin. We also include analytical data from Pennsylvania anthracite and petrographic data from the graphite deposits. For each of the coal samples we obtained proximate and ultimate analyses, petrographic and vitrinoid reflectance data, and partial chemical analyses of mineral matter. Petrographic and mineral matter analysis were carried out at the U.S. Steel Research Laboratory under the direction of Ralph Gray, while the chemical analyses of coal were obtained from U.S. Steel as well as compiled from various sources (Lyons and Chase, 1981). Information (petrographic and microprobe analysis) is also available for associated metasediments (Murray, unpub. data), and to a lesser extent for the higher grade graphite deposits; and this data will also be discussed. A brief description of each sample locality is given below.
1 Pennsylvania anthracite. Samples were collected from the western part of the southern field, and are included here for comparison:
2 Mansfield, Mass. The samples analyzed come from a 1 meter seam of high ash coal obtained during drilling in the vicinity of several small mines. Metamorphic grade is subgreenschist.
3 Plainville, Mass. The sample was handpicked from the seam currently being quarried. Other than possibly being lower in ash than the bulk seam (a carbonaceous shale), it is representative of material being mined. This subgreenschist grade sample is the lowest metamorphic grade sampled to date.
4 Somerset, Mass. The sample was obtained from a 4 meter coal seam encountered in drillcore near a major fault in the southeastern part of the basin (i.e. directly underneath the Brayton Point fossil fuel power plant). Metamorphic grade = lowest greenschist.
5 Bristol, R.I. Samples are from a 1 meter thick seam encountered in drilling and possibly correlative with a nine meter seam, that was drilled 100 meters away. The coal occurs within a kilometer of a horst of basement granitic gneiss that may be the locus of a local metamorphic high in the basin, although the metamorphic grade for this region is also lowest greenschist.
6 Portsmouth, R.I. The samples come from a 1 meter seam from drillcore; other seams in the vicinity range to 4 meters thick. Drilling was in the vicinity of (and possibly correlative with) the coal seams of the largest mine in the Narragansett Basin. The metamorphic grade is lowest greenschist.
7 Cranston, R.I. The samples come from the 6 meter seam mined intermittently until 1959. The rocks are in the chloritoid zone.
9 Tower Hill, R.I. The samples come from a small nearly inaccesible graphite mine in the sillimanite-kspar zone. The well developed cataclastic fabric seen in the walls of the mine are typical of the shearing that appears to be localized in the vicinity of the coal and graphite deposits, and which is seen at Fenners Ledge (Stop 5).

Field Relationships

Seams are typically thick (to 10+ meters), laterally discontinuous, and occur in irregularly shaped bodies. Most of the variations in thickness apparently are structurally controlled, based upon our own observations, as well as old mine reports. The latter often refer to seams (i.e. at Mansfield, Portsmouth, and Cranston) as "pinching and swelling" or characterized by the presence of ellipsoidal "rolls" that have their long axis subparallel to the regional trend of folds. At the only place where coal is actually being quarried (Stop 4) the thickness varies from 10+ meters at the hinge of an anticline to zero meters along the limbs (<100 meters across strike). At Bristol R.I. detailed drilling suggests that again thickness varies from 10+ to <2 meters over very short distances (i.e. <70 meters), and that the coal may have broken loose from its stratigraphic position and migrated along fault surfaces. Extreme variations in seam thickness may also be sedimentologically controlled.

Megascopically, all coals are strongly deformed, and deformational style varies from isoclinally folded in high ash coals to relatively more brecciated and veined in low ash varieties. In many cases, the coal appears to have become decoupled from the enveloping rock, and thick veins of fibrous quartz and micas ("asbestiform quartz") often occur along the roof and floor contacts and within the coal. The presence of dragfolds within the coal and slickensided surfaces along faults subparallel to contacts also suggests that the coals have undergone shearing. Presumably this is at least in part a consequence of the strong contrasts in competency between the coal and the surrounding sediments (usually sandstones or conglomerates).

In hand specimens, the coals have a dull, graphitic to submetallic appearance, and due to a pervasive secondary depositional carbon and brecciated fabric, are often sooty when handled. The brecciated to friable nature of the coals and the presence of substantial amounts of primary and secondary mineral matter cause the coal to break with an irregular fracture. Conchoidal fracture, which is distinctive of most anthracites from Pennsylvania, can only be observed on small surfaces (if at all) in Narragansett Basin coals. Coals that are relatively low in syngenetic mineral matter tend to break up with a hackly fracture, whereas coals with high concentrations of syngenetic phyllosilicate mineral matter may break with a preferred orientation either along original bedding or slickensided surfaces (Fig. 5). The brecciated coal occasionally appears to have a closely spaced cleat, however, careful examination suggests that this "cleat" is in some cases a cubic cleavage characterized by the alignment of graphite and mica along surfaces roughly parallel to to the axial plane of regional folds. The cleats, as well as "polished" surfaces (i.e. ones characterized by smooth coatings of graphite) are concordant with regional tectonic fabric, and similar relationships have been reported from deformed high rank coals from Pennsylvania (Hower, 1980), Australia (Stone and Cook, 1980), and China (Fen and others, 1979). By chloritoid grade (Stop 5) the coal megascopically resembles a graphitic schist, although microscopically it is still recognizable as coal. At higher grades (Stop 6 & Tower Hill) the transformation to graphite is essentially complete, and all organic matter has recrystallized. The graphite in these amphibolite facies rocks occurs as finely disseminated matter, and as veinlets (< 0.1mm thick) that define schistosity. Larger masses of graphite (originally coal seams) are brecciated, with intense shearing along contacts and with a complex network of veins (Stop 5).

The coals are also often friable and hydroscopic, due to a combination of: 1) granular character, 2) secondary graphitic depositional carbon, 3) microbrecciation, 4) removal of mineral matter through leaching, and 5) softening and pore formation in thermally altered coals. The coals may hold more than 20 wt.% moisture if left out in damp air.

Table 1. Coal chemistry and vitrinoid reflectance of selected samples from the Narragansett basin, southeastern New England and the Pennsylvania anthracite basin. Analyses compliments of R.J. Gray, United States Steel.

	1 Pennsylvania anthracite southernfield		2 Mansfield, MA. drillhole # 8		3 Somerset, MA. drillhole # 33		4 Portsmouth, R.I. drillhole # 2		5 Bristol, R.I. drillhole # 51		6 Cranston, R.I. Budlong mine
	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	as rec'd	dry basis	dry basis
Ultimate analyses											
carbon	78.84	81.41	53.27	55.27	77.52	78.89	60.99	68.79	63.87	64.03	
hydrogen	3.05	2.89	.91	.51	.86	.68	1.40	.15	.53	.50	
nitrogen	.75	.76	.21	.22	.28	.28	.23	.26	.16	.16	
oxygen		1.17		.58		1.27		.00		.33	
sulphur	2.98	3.04	1.02	1.06	.30	.31	.050	.06	.05	.05	.002
ash	10.52	10.73	40.82	42.36	18.25	18.57	27.26	30.75	34.84	34.93	
moisture	1.93		3.64		1.74		11.34		.25		
Surphur forms											
FeS_2 as S			.78	.81	.25	.25	.022	.025	.06	.06	
SO_4 as S			.12	.12	.004	.004	.005	.006	.002	.002	
organic S				.13		.06		.03		.01	
Proximate analyses											
volatile matter				4.9		4.6		3.1		3.6	2.4
fixed carbon				51.8		77.7		64.1		61.8	78.1
ash				43.3		17.7		32.8		34.6	19.5
Vitrinoid reflectance											
mean maximum	3.52		6.48		7.19		4.47		5.98		
mean minimum	2.61		3.93		3.70		2.75		2.64		
mean bireflectance	.91		2.55		3.49		1.72		3.34		
HGI			94.5		50		47.5		38		

Figure 5. Sketch of deformational and metamorphic textures in coals. Both sketch are derived from reflected light sections viewed at 400X. Fig. 5A; Low primary ash coal (shaded pattern) that has been brecciated with displacement and rotation of fragments resulting in volume increase. Secondary depositional graphitic carbon (stippled pattern) coats the fragments and mineral matter (clear pattern) fills the voids. From Portsmouth, R.I. Figure 5B; High primary ash (clear pattern) and coal (shaded pattern) that has undergone folding accompanied by brecciation of coaly layers. Masslite quarry.

Table 2. Mineral matter in high rank coals. Analytical data courtesy of F.E. Huggins, Huffman, and G.P. Gray, Research Laboratory, United States Steel Corp. tr<4 particles or 0.3 wt. % found; *Principally mixtures of common mineral phases; + Manganese to 5% by weight of particles.

	Penn. Anthracites		Narragansett Bassin Anthracites				
	10348 Southern	*10349* Field	10398 Bristol, R.I.	10399 Portsmouth, R.I.	10400 Mansfield, MA.	10401 Somerset, MA.	4889 Cranston, R.I.
Quartz	8	8	28	60	18	32	25
Kaolinite	5	0.6	tr	tr	tr	tr	—
Illite/Muscovite	26	36	39	13	34	24	43
Chlorite/Chamosite	0.5	0.7	6	3	7	8	9
Montmorillonite	tr	tr	tr	1	—	tr	tr
Mixed Silicates	19	23	23	10	29	9	12
Pyrite	31	23	—	—	4	3	tr
Fe Carbonate/Oxide/)** Metal/Oxyhydroxide)	2	0.5	1	4	0.7	1.4	2
Calcite	1	0.5	0.3	3	0.3	7 +	tr
Ankerite	0.4	tr	—	1	—	9 +	—
Fe Sulfate	1	—	tr	—	0.3	tr	2
Ca Sulfate	—	0.4	—	—	—	—	—
Rutile	—	tr	0.7	tr	—	tr	tr
Apatite	—	tr	1	tr	—	tr	—
Unknown Others*	6	8	1	5	6	6	7

Simplified Classification and Optical Properties of Metamorphosed Coals and Carbonaceous Shales

Narragansett Basin, Massachusetts and Rhode Island

COAL CLASS	Coalification History	Metamorphic History	Intensity of Deformation	Distinguishing Petrographic Properties	Temp. C°
'NORMAL' ANTHRACITE and META-ANTHRACITE	'Normal' Coalification	Diagenetic(?) Regional Metamorphism	Moderately Deformed	High vitrinoid max. reflectance values resulting from glassy surface texture High reflecting 'organic inerts' Regular fracture surface	>180-200
'THERMAL ANTHRACITES'	'Abnormal' Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Apparent low vitrinoid max. reflectance values resulting from granular texture Low reflecting 'organic inerts' Softening and pore formation Incipient mosaic texture Graphitic depositional carbon	>350
BURNT COAL	'Abnormal' Oxidizing Conditions Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Irregular polishing surface Brownish hue	>350
NATURAL COKE	'Abnormal' Reducing Conditions Coalification	Regional and/or Contact Metamorphism	Highly Deformed	Mosaic anisotropic texture Coke pores High bireflectance	>350
GRAPHITE	(?)	Regional and/or Contact Metamorphism	(?)	High bireflectance	(?)

Figure 6. Optical properties of Narragansett basin coal. Compiled from Raben and Gray, 1979.

Petrographic Analysis

Petrographic studies of textural relationships have proven to be the single most useful parameter in terms of providing insight into the nature and history of the coals, and representative textures are shown in Figure 5.

The mean maximum reflectance of vitrinites (R_oV) was measured to determine rank (Table 1). The reflectance of vitrinite in normal anthracite ranges from 2.5% to 7.0%, and those above 7.0% are considered meta-anthracites. The mean maximum reflectance for vitrinites in samples of Narragansett Basin coals range to a high of 7.62% in green light in oil (Table 1).

Vitrinites observed include both textured and untextured varieties. In some instances (Bristol, Portsmouth, and Cranston) the coal has been thermally altered, as evidenced by the occurrence of incipient mosaic texture, limited softening and pore formation. Most of the coals show some degree of thermal as well as mechanical alteration. As a result of this alteration, there often has developed microstructural domains, on a submicron scale, that are revealed with SEM imagery. These domains are smaller than the sensing area used for ASTM standards for reflectance determinations, and thus make of questionable value standard reflectance measurements. In particular, the apparent decrease of R_oV in the coals found in areas of relatively high metamorphic grade (e.g. Cranston, Bristol, and Portsmouth) can be explained in terms of the preferential development of microstructural domains. The "organic inert" components (fusinite and semifusinite) are less reflecting than associated vitrinite, especially in those coals displaying alteration features. This is is in marked contrast to maceral reflectivity patterns observed elsewhere (Stach and others, 1975). In some samples of coals that display granular texture within vitrinitic portions, there are associated materials structurally similar to natural coke with mosaic anisotropic texture and "coke pores". Such features have been rather exhaustively studied (because of their economic importance), and their formation is believed to require temperatures $T \geq 400^{\circ}C$ in natural systems.

Two gross categories of coal may be distinguished in the Narragansett Basin, and together they are have been designated "meta-coals" (Raben and Gray, 1979). In addition to the features described below, both categories are variably deformed and annealed. The first consists of relatively normal anthracite and meta-anthracite, and is characterized by coal from Plainville, Mansfield, and Somerset. These coals have high R_oV values (generally greater than 6.0%) resulting from a glassy surface texture, high reflecting "organic inert" components, and regular fracture surfaces. Except for the degree of deformation and slightly higher rank, they are similar to Pennsylvania anthracites, and standard vitrinoid reflectance measurements are considered a reasonable rank parameter for them. The second category consists of all coals that have been not only deformed, but thermally altered, and it includes thermal anthracites, burnt coal, and natural coke (Figure 6). Thermal anthracites have low R_oV values resulting from a granular surface texture, low reflecting "organic inert" components, irregular fracture surfaces, incipient mosaic texture, variable softening and pore formation, and graphitic depositional carbon. Burnt coals show an irregular polishing surface and brownish hue. Natural cokes have high bireflectance, coke pores, and mosaic anisotropic texture. There is some indication that the material resembling natural coke may have had an origin that was at least in part tectonic and not entirely thermal (R. Gray, pers. comm. 1979). In this respect, the coals are similar to ones described from regionally metamorphosed terrane in New Zealand (Diessel and others, 1978).

The changes described above are essentially completed by the attainment of biotite zone metamorphism. With increasing metamorphism, the "coal" behaves as a chemically inert and mechanically brittle material, and only two changes are apparent in thin (or polished) section. The first is the evolution of vein fabric and assemblages. Through chloritoid grade (Stops 2 & 5), the veins consist primarily of fibrous quartz, and slightly lesser amounts of "asbestiform" white mica + chlorite (see Rutstein, 1979, for a discussion of this mica intergrowth from the Portsmouth area). With increasing metamorphism (Stop 6), the fibrous nature of the grains gives way to a more equidimensional fabric consisting of unstrained, equant grains. The vein assemblages also change, and at Tower Hill consist of sillimanite plus complex intergrowths of mica, garnet, and staurolite (Grew and Day, 1972). The other change consists of the appearance of graphite schistosities, which become increasingly well developed with increasing metamorphism. Moreover, they occur not only in pelites, but also in coarse sandstones. These graphitic "microveins" are considered to have formed by the precipitation of carbon out of a gas phase (exhumed from nearby coal ?).

Proximate And Ultimate Analyses

Table 1 presents representive chemical analyses of Narragansett Basin coals, and the reader is directed to Lyons and Chase (1981) for a compilation and discussion of proximate and ultimate analyses obtained through 1979. Figure 7 shows the relation between fixed carbon and ash. The rank patterns based upon these analyses are, in general, in conflict with that predicted from metamorphic grade and petrography (Raben and Gray, 1979; Murray and Raben, 1980; Lyons and Chase, 1981), and there are several explanations. All of the Narragansett Basin coals are high in ash, and this will skew Parr-formula corrected analyses towards misleadingly high rank values (Quinn and Glass, 1958; Lyons and Chase, 1981). Unlike other coals, the ash is mainly secondary, and occurs as a dense network of veins. Volatile matter in the Narragansett Basin coals is also misleading because it includes a) water absorbed on brecciated surfaces, b) water structurally bound in mineral matter, and c) the predominance of non-combustible gases such as CO_2. Hydrogen content may be the best indication of rank, as it best correlates with rank patterns expected from petrographic studies of coal and rock.

Taking both chemical and petrographic data into account, the coals most simply classify as; 1) variably deformed, high ash anthracites to meta-anthracites in the northern half (i.e. Plainville, Mansfield, & Somerset), and 2) deformed, moderate to high ash, meta-anthracites and thermally altered carbonaceous material in the southern part of the basin (i.e. Cranston, Bristol, & Portsmouth).

Mineral Matter

Table 2 presents modal abundance of minerals found in the coal, as determined by automated scanning electron microspcopy (i.e. SEM-AIA) at the Research Laboratory of U.S. Steel. Iron-bearing phases were further identified using Mossbauer spectroscopy (Murray & Raben, 1980), and the results indicate the presence of metallic iron. This is suprising, implies values of f_{O2} well below the graphite buffer, and may be related to the reducing effect of a (methane-rich) gas phase released from the coal during deformation. Except for the initial degassing, the coal behaves as a relatively inert, brittle material during metamorphism. One consequence is the development of veins connecting fragments of coal, probably because the coal acts as a "sink" for silica and other components released into the fluid phase via pressure solution operating upon the surrounding quartz-rich sandstones. To a lesser extent, the veins also contain illite and chlorite as submicroscopic intergrowths (Rutstein, 1979) along microfractures, and this intergrowth has in the past been incorrectly classified as "asbestiform quartz" Because of the unusually complete sample base (outcrop and drillcore), one may examine the changes that occur in fabric and mineral chemistry of the veins through the entire metamorphic spectrum, and possibly chart the strain history as well.

Graphite Crystallinity Studies

Several X-ray analyses of organic material from the coals have been carried out (Quinn and Glass, 1958; Grew, 1974; Wintsch and others, 1980), and all have shown considerable scatter in graphite crystallinity values in samples from greenschist facies. One explanation for the variation may be that the analyses were performed on polygenetic carbon, as petrographic studies show that secondary depositional graphitic carbon coats fragments of coal (Raben and Gray, 1979) and grain boundaries in surrounding rocks. In fact, petrographic studies of Narragansett Basin coals suggest the presence of three distinct carbon-bearing materials: 1) original material still recognizable as coal macerals; 2) the depositional graphitic carbon that apparently precipitated out from a gas phase (that was probably generated by the release of methane from the coal) coats fragments of coal and mineral grains, and defines schistosities in adjoining rocks; and 3) new carbon nucleating directly within the surfaces of macerals as evidenced by the presence of mosaic anisotric textures. This range in structural states of carbon is maintained through the highest grades of metamorphism; and at Tower Hill a detailed study of one "homogeneous" fragment of graphite showed that the crystallinity decreased systematically from rim to core (R. Wintsch, pers. comm., 1980). This range of crystallinity occurs in a sample associated with metasediments that were metamorphosed to P=5kbar and T=600+°C (Grew and Day, 1972; Murray, unpub. data).

THE RESPONSE OF ORGANIC MATERIAL TO METAMORPHISM AND DEFORMATION

We have used the petrographic observations presented earlier plus geological considerations to construct the probable sequence of events that resulted in the coals as we now see them. Figure 8 shows a preliminary correlation of coal rank with various metamorphic parameters, and will provide a framework for the discussion of the evolution of the coals. The tentative model for the evolution of the Narragansett Basin coals holds that prior to the onset of regional metamorphism and deformation, coalification varied from low volatile bituminous to anthracite, with rank possibly increasing to the north. Folding and faulting were initiated throughout the basin, with pressure solution and degassing of the coals during brecciation important mechanisms. Depending upon the ash content, the coal responded to deformation primarily by disharmonious folding (high ash) or brecciation (low ash), as shown in Figure 5. Presumably the migration of brecciated coal fragments towards structurally favorable positions (fold hinges) began as well. With the onset of regional metamorphism and deformation the coals were altered to either high rank anthracites and meta-anthracites or thermally altered (i.e. they left normal coalification

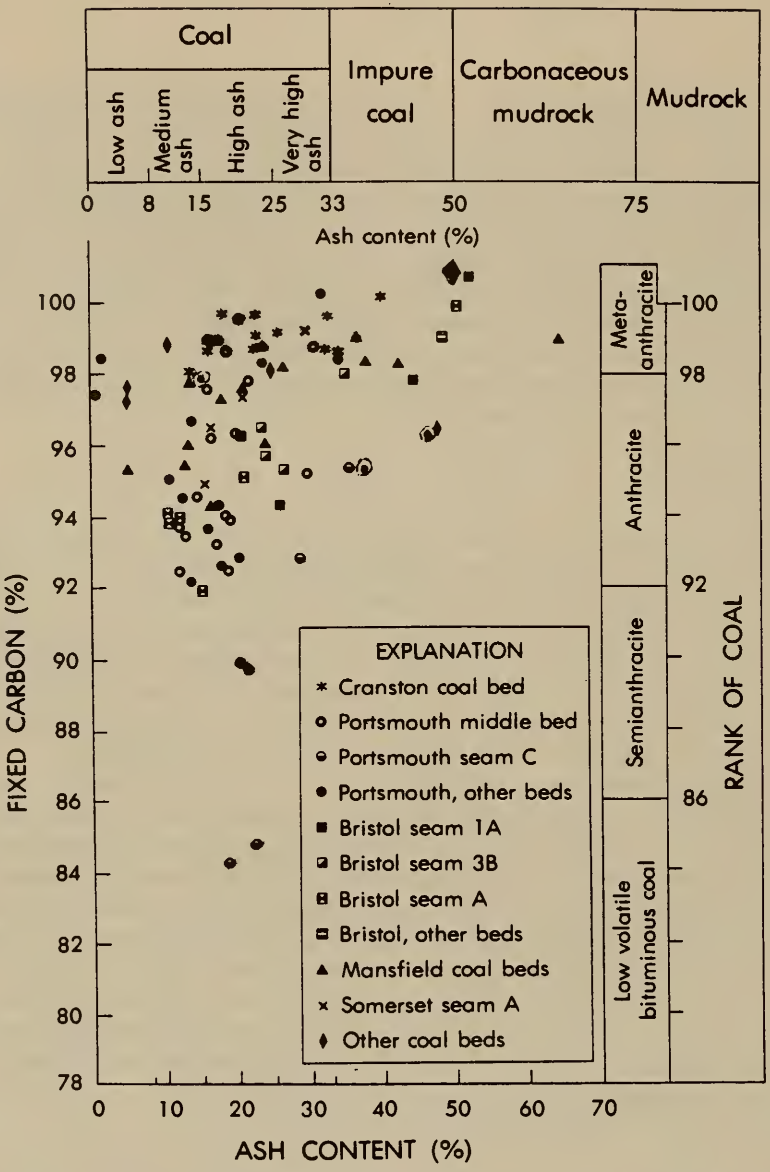
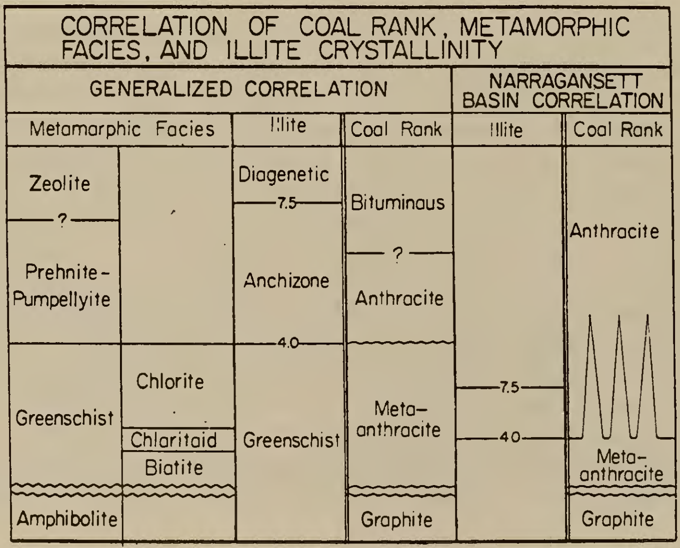


Figure 7. Relationship between fixed-carbon content (Parr-corrected) and as-received ash content of 90 coal samples from the Narragansett basin. Modified from Lyons and Chase (1981).



CORRELATION OF COAL RANK, METAMORPHIC FACIES, AND ILLITE CRYSTALLINITY

GENERALIZED CORRELATION				NARRAGANSETT BASIN CORRELATION	
Metamorphic Facies		Illite	Coal Rank	Illite	Coal Rank
Zeolite		Diagenetic	Bituminous		Anthracite
?		7.5			
Prehnite-Pumpellyite		Anchizone	? Anthracite		
		4.0			
Greenschist	Chlorite	Greenschist	Meta-anthracite	7.5	
	Chloritoid			4.0	Meta-anthracite
	Biotite				
Amphibolite			Graphite		Graphite

Figure 8. From Murray and Raben, 1980.

paths) coals; which type was attained being a function of the rank and/or kinetics.

With the onset of more rapid and intensive dynamothermal metamorphism, the coals developed incipient mosaic textures, granular texture, coke structures, and secondary graphitic depositional carbon. The above features were established by the chloritoid grade, and at higher metamorphic grades they become further accentuated, culminating in the development of graphitic schist. The presence of softening textures at Bristol and Cranston may mean that the metamorphism was rapid. There are also several details of the evolution of the coals that are germane to discussions of the overall metamorphic history of the area.

1. The secondary depositional graphitic carbon coats brecciated coal fragments and mineral grains in the surrounding sediments, in the latter case it may convert a sediment originally a shale into a carbonaceous shale. This carbon was precipitated out of a gas phase that was probably methane-rich and derived from gas released from the coal during brecciation. The reason it precipitated could be either increasing metamorphism or interaction with a more oxidized environment associated with the surrounding sediments.

2. SEM and Mossbauer spectroscopy studies of the iron bearing phases in the coals identified the presence of metallic iron and other highly reduced phases (Murray and Raben, 1980), suggesting that the fluid phase in coals and their immediate surroundings may well be buffered at values of f_{O2} well below the graphite buffer. The cause of such low values is presumably the abundance of CH_4 in the gases released from the coal with deformation. Regardless of the mechanism by which such highly reducing environments are maintained, their effect on mineral equilibria in adjacent pelitic rocks should be substantial. And, it is apparent that the degradation and homogenization of organic material with associated sediments during progressive metamorhism is a complex process, and one that needs to be much more completely evaluated before various meaningful correlations can be made between coal rank and mineral parageneses (Zen and Thompson, 1974; Murray and others, 1979; Murray and Raben, 1980) or illite crystallinity (Wolfe, 1976; Rehmer and others, 1978; Kisch, 1980).

Clearly, the duration and rate of metamorphism are important parameters in the evolution of the coal. In addition, the rank at the onset of regional metamorphism and structural setting of the coal exert strong controls on the end products. A complex interplay among metamorphism, strain history, and primary differences in coal character have resulted in unusually large variations in coal petrography and chemistry at a given locale, as well as throughout the basin. The classification and characterization of Narragansett Basin coals is made particularly difficult because of the ubiquitous presence of the following features; non-combustible gases, secondary depositional carbon, hydroscopic nature, and presence of thermally altered material. Thus, one must reevaluate the validity of classification systems based upon standard rank parameters when applied to very high rank and/or thermally altered coals. Moreover, as pointed out in Quinn and Glass (1962) and Lyons and Chase (1981), the very high ash concentrations (both primary and secondary) in these coals generate additional problems in the use of rank classifications based upon Parr-formula corrected chemical analyses, which are a standard criteria for coal classification.

ACKNOWLEDGMENTS

We would like to thank Ralph Gray for advice on the interpretation of petrographic features in the coals, and for generously providing analytical data on them. Murray is grateful for support from NSF Grant EAR-7904882 and from a grant from Boston University.

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STOPS

TOTAL
MILEAGE

STOP 1

Ranger Hall, U.R.I. The following topics will be covered.
20 minutes. A synopsis of the geologic history of the Narragansett Basin, with an emphasis upon the history of mining and related activities, and upon the evolution of organic material with progressive metamorphism and deformation.
2) 40 minutes. A "cram course" in coal (and graphite) petrology, with the focus being a discussion of the petrographic features that are unique to Narragansett Basin coals.
3) 30 minutes. Examination of drillcore and other samples of carbonaceous material from now inaccessible mines and prospects.

Leave Kingston on Rte. 138 East. Go 4 miles and turn north (left) onto Rte. 1. Go approximately 2.5 miles and take Exit for Rte. 138 East to Jamestown and Newport. Stay on Rte. 138, following signs for the Newport Bridge. Cross the Jamestown Bridge and follow Rte. 138 to the Newport Bridge (toll of $2). After crossing the bridge, take the Rte. 138 exit (the second one). The exit ramp ends at a stop sign across from Jai Lai (Hi Li). Turn right; log starts from this stop sign.

0.0 Hi Li parking lot.
0.6 Stop light for Rtes. 138 and 114; turn right and follow Rte. 114 through 3 stop lights.
7.3 Turn left onto Cory Lane (first left after flashing yellow light), following signs for Portsmouth Abbey School.
8.1 Bear right after the Portsmouth Abbey Hockey Rink, and continue into the school's parking lot. A path leads down to boathouse on shore.

STOP 2

Shoreline exposures of Rhode Island Formation, northwest Aquidneck Island. Nearly continuous outcrops of fossiliferous slate, siltstone, sandstone, and coal occur both north and south of the Abbey boathouse. (This is the same as STOP 3 of the trip lead by Burks and others, this volume.) Approximately a mile to the north can be seen the rectangular tower of the Kaiser Aluminum plant, which was built over the southern (of two) shafts of the Portsmouth coal mines (Stop 3).

During 1980 two holes were drilled on the grassy field at the northeast end of the outcrop, on the Portsmouth Abbey School property. The drillsites were chosen for the following reason. Since the strata along the shoreline were believed to be for the most part upright and of the same approximate orientation as the coal seams mined to the north (i.e. N30E 20-30SE), the drill sites would, hopefully, sample at least part of the "stratigraphic" section between the shoreline outcrops and the mined area. The first hole encountered a 2 meter thick seam petrographically similar to the coal mined at Portsmouth. An additional drillsite 100 meters away was designed to obtain another sample of the coal.

Sedimentologically, the rocks are finer grained than most of of the Rhode Island Formation seen elsewhere, and they may represent either lacrustrine or floodplain deposits. A well-developed floral assemblage from the middle of the strip of outcrop north of the boathouse indicates that the sediments are Westphalian D or Stephanian A in age. Coal petrography (Murray and others, this volume) coupled with routine petrography suggests temperatures $T=400^{\circ}C$ were attained during metamorphism.

Both strips of outcrops are characterized by N20E 30SE subparallel bedding and cleavage, with the cleavage being axial planar to tight F1 folds. Despite the presence of grade bedding, cross stratification, and flattened erosional contacts, it is suprisingly difficult to assign a general younging direction to the outcrop. If one accepts the "concensus" opinion that the beds are for the most part upright, then one can infer a position on the upright limb of a tight, NNE trending overturned syncline. The hinge may be along the eastern edge of the island, an orientation of bedding consistent with the presence of nearly flat (dip $<15^{\circ}$) beds encountered during drilling there. Alternatively, folding may be on a substantially smaller scale, with a synformal hinge no further than a kilometer to the east (S. Mosher, pers. comm., 1981). Tight, parasitic D1 folds are best displayed at the northern end of the northern outcrop. Open, E-W trending folds (D3 ?) are cut by NE striking, NW directed thrusts at the southern outcrop. Pressure solution phenomena are well developed, and of particular interest are fibrous quartz-mica veins that formed in coal and carbonaceous slates seen in the southern strip of outcrop.

Turn to left when leaving the parking lot and retrace route to Rte. 114.
8.9 Intersection of Rte. 114 and Cory Lane
Proceed north on 114 to Willow Lane.
10.3 Intersection of Rte. 114 and Willow Lane; turn right onto Willow Lane and drive straight ahead, crossing railroad tracks and passing (to the left)
11.2 the Kaiser Aluminum plant.
At the pavement's end continue on the dirt road 0.2 miles to the gate on the left side of the road.

STOP 3
Mine dump at the site of the Portsmouth Coal Mine. Specimens of meta-anthracite may be collected here, the site of the largest coal mine in the basin.

The mines on northern Aquidneck Island were worked intermittently during the eighteenth through early twentieth century, and approximately 1.13 million tons of coal were removed from here between 1860 and 1913. Mining was mainly confined to the middle of three coal seams, and this seam was worked from two slopes, 1800 feet apart, that extended down dip. The seams averaged 36 inches, although lenses up to 12 feet were common. This is the location of samples collected for chemical analyses (Tables 2 & 3), isograd classification (Quinn, 1971), and crystallinity studies (Quinn and Glass, 1962; Grew, 1974).

13.5 Return to Rte. 114 by retracing the route to Cory Lane, and proceed north.; Rte. 114 becomes Rte. 24.
Take Rte. 24 north to I-195 (Fall River).
24.1 Go west on I-195 (towards Providence)
27.8 Rte. 103 exit. To your left (south) can be seen the smoke stacks of the Brayton Point Power Plant, the largest fossil fuel (coal now, previously oil) burning plant in New England. Three meter thick coal seams (the analyses labelled Somerset in Tables 1 & 2) were encountered during drilling here, approximately 270 meters under the plant.
Continue west in I-195.

30.2 Rte. 6 (Swansea) exit. The outcrops of Dighton Conglomerate seen along the southeast expressway ramps were described in STOP 2 of the 1976 NEIGC led by Skehan and others. They are part of the southernmost of the three synclines containing Dighton at the core (see Fig. 1).

41.2 Continue west on I-195 to intersection with I-95.; bear right, in order to take I-95 north.

52.0 Rte. 123/I-95 (Norton-Attleboro exit). Outcrops along the exit lane are of Dighton Conglomerate, in the northern most of three synclines that contain this unit.
Continue north on I-95.

56.3 Series of roadcuts in Wamsutta Formation.

59.5 Continue north to intersection with I-495.; take I-495 west.

64.0 Exit from I-495 onto Rte. 1A, and head south (left turn at end of exit ramp).

65.4 Turn right onto Cross Street, and follow signs to Masslite Broken Stone Quarry.

66.0 Park in visitor's parking lot, and check in at the front office. This stop is on private property, and never accessible without permission. At the time of preparation of this article, the coal seam could be best seen by taking the dirt road to the right-hand excavation. This is also the best place to find good examples of plant fossils and primary sedimentological features. In contrast, faulting and folding is best observed in the other pit, to the left. This is also a stop in the Hepburn and Rehmer article in this volume, and is STOP 3 of a previous NEIGC (Lyons and Chase, 1976).

STOP 4

Masslite quarry, Plainville, Mass. This quarry (Fig. 9; also see Fig. 3 of Lyons and Chase, 1976) represents the best exposure of coal stratigraphy in the basin, and consists of a generally fining up sequence below the coal and coarsening up sequence above it, with a total stratigraphic thickness of 150 meters (in terms of present exposure). Large boulders have broken away from the quarry wall, and they conveniently display all of the pertinent sedimentological textures and plant fossils found in the quarry.

The coal seam is tectonically thickened, as evidenced by the presence of isoclinal folds in the coal, and quartz- and mica-rich veins occur along numerous shear zones. In contrast, folding and faulting in the surrounding clastic sediments is less intense. Apparently, differential movement has taken place along both the upper and lower contacts of the coal seam, and one of the results has been to tectonically thicken the coal. The coal seams were probably originally quite lenticular in shape (i.e. they were distinctly non-tabular) as well as significantly weaker than the surrounding coarse grained clastic sediments, and this may be at least in part responsible for the structural complexity observed in the vicinity of the seam.

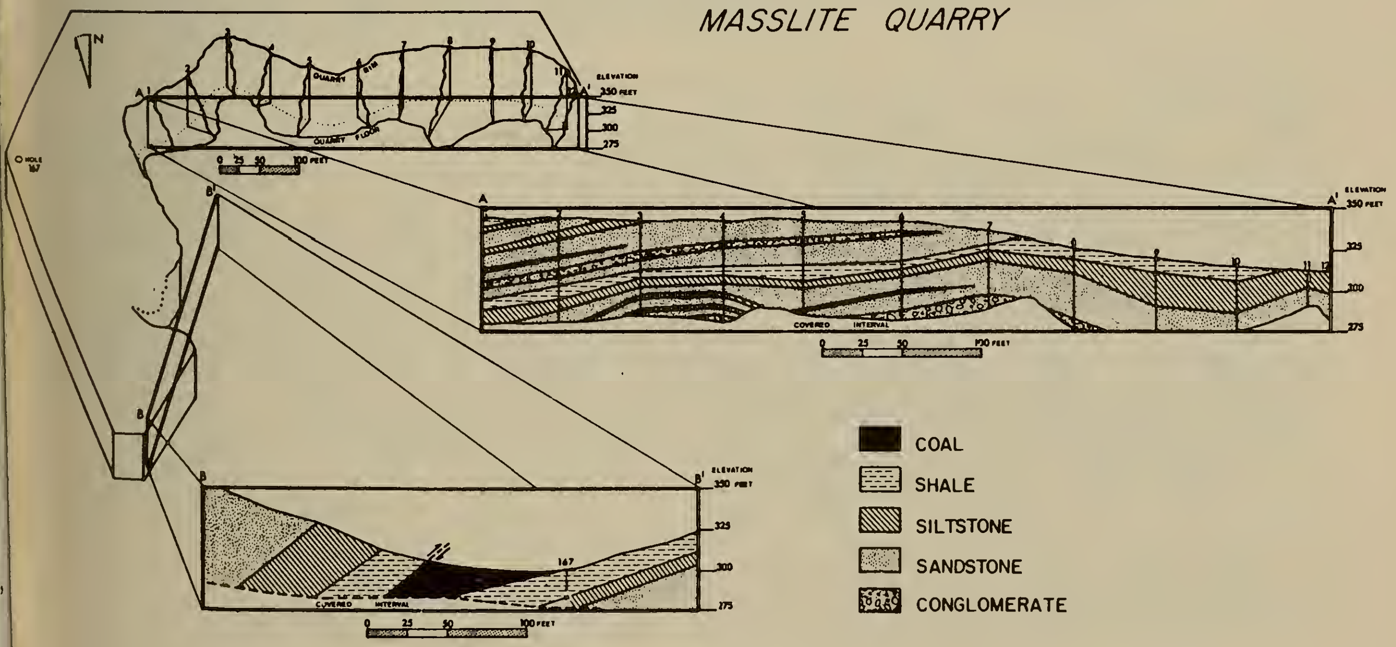
The shale below the coal has rooted horizons, and the siltstone below the shale is extremely fossiliferous. Coarser grained lithologies contain branches, stems, and rip clasts of finer grained lithologies. A detailed sedimentologic and stratigraphic study of the drillcore and outcrop in the quarry has recently been completed (Severson, 1981; Severson and Boothroyd, 1981). They concluded that the Rhode Island Formation represents medial to distal humid alluvial fan environments and the overlying Dighton conglomerate repesents proximal alluvial fans. The coal deposits are presumed to have developed on abandoned bar and with another recent study of the sedimentology of the basin by Cable (1981). This quarry has also provided the greatest number of plant fossils of any locale of the basin, as shown in (Fig. 4).

The rocks exposed here represent the least metamorphosed part of the basin studied to date. Illite crystallinity data (Hepburn and Rehmer, this volume), coal petrology (Raben and Gray, 1979) and petrography (Murray, unpub. data) indicates that the rocks are in the anchimetamorphic zone.

The coal and carbonaceous shale seam is being actively quarried and mixed with the adjacent shales and carbonaceous shales, and used in the production of lightweight aggregate. Lightweight aggregate is a "popcorn"-like substance that is produced by the ignition of the coal and shale. If anthracite from Pennsylvania were to be used instead of the indigenous material, the Masslite quarry operation would not be profitable. We will tour the proccessing plant.

73.5 Return to the intersection of I-95 and I-495, and take I-95 south.
94.7 Take Rte. 10 north (Exit 16; Cranston, R.I.).
95.6 Turn left (south) on Reservoir Ave.
96.3 Turn right (west) on Park Ave.
96.8 Turn right (north) on Gansetts Ave; this becomes Cranston Ave.
Turn left into the NHD Hardware lot; if you run into Rte. 10 again, you have gone too far.
The outcrops are to the left and rear of the hardware store.

Figure 9. Geologic relationships in the northern part of the Masslite quarry.



STOP 5
Fenners Ledge, Cranston, R.I. The stop consists of the series of small cliffs and outcrops south and west of the NHD Hardware store. The rock types consist of sandstone, siltstone, slate, and graphite lenses, with the latter largely covered up. Chloritoid, white mica, chlorite, quartz, and ilmenite are the main metamorphic minerals, and X-ray data on micas and graphite from this site may be found in Quinn and Glass (1962) and Grew (1974).

The structure is unusually complex for this part of the basin, perhaps because of its proximity ot the basin's margin or the presence of faults. The general trend of bedding and S1 is N35E 65SE, with variations in strike from N0E to N50E due to later gentle folding. Fine rods developed on S1 trend N32E HORIZONTAL, and are folded about N65E 42NE axes. A crenulation cleavage is also present. A series of faults subparallel to S1 have both dip-slip and strike-slip movement, based upon the orientation of coarse quartz fibers. Along these fault surfaces, S1 is folded and crenulated along primarily NE trending axes.

101.3 Return to I95, reversing the directions used to get here.
Head south on I-95.
110.3 Take Rte. 4 south (get in the left lanes for exit).
Rte. 2 joins Rte. 4, and the road changes to a four lane undivided highway; continue south to rotary
Stay on Rte. 4, heading towards beaches.
120.3 Rte. 1 joins Rte. 4.
Take Rte. 138 east, towards Newport.
Cross over the Jamestown Bridge to Conanicut Island.
124.7 Park at the east end of the Jamestown Bridge, (near Jamestown Shores Motel), which connnects Conanicut Island with the western shore of Narragansett Bay, and take path down to the shore beneath the bridge.

STOP 6
Rhode Island Formation, Jamestown. Lithologies present include carbonaceous schist, conglomerate, and sandstone. The schist contains staurolite, garnet and biotite porphyroblasts in a matrix of biotite, muscovite, quartz, ilmenite, and dispersed organic matter. The porphyroblasts are post-S1, but older than a well developed crenulation cleavage and associated retrograde metamorphism. The structure is discussed in more detail in Burks and others (this volume; STOP 5). Probable Stephanian A plant fossils (Fig. 2) have been identified approximately a kilometer to the south, and other plant fossil debris occurs along the northwest coast of the island. X-ray data on graphite are given in Grew (1974). An abandoned (and almost completely inaccessible) graphite prospect is located roughly 2 kilometers to the north, along the shore, and is associated with a calc-silicate horizon. Petrographic analysis from this stop and the prospect are in progress, and preliminary results suggest the following chronology: 1)D1 accompanied by metamorphism to biotite grade; 2) growth of garnet, then staurolite, and finally biotite porphyroblasts randomly oriented on S1 surfaces; 3) development of crenulation cleavage defined by graphite; 4) retrograde chlorite grade metamorphism. Veins in brecciated coal are quartz + muscovite.

--- END OF TRIP ---

SELECTED MINERAL COLLECTING SITES IN NORTHEASTERN RHODE ISLAND

by

Ralph L. Carr[1] and John O. Edwards[2]

[1]25 Farnum Road, Warwick, R.I. 02888

[2]59 Irving Avenue, Providence, R.I. 02906
(Rhode Island Mineral Hunters, Inc.)

Introduction

The township of Cumberland at the northeast corner of Rhode Island is not so famous mineralogically as Cumberland in England; however there is enough of interest in this town and in Lincoln - the adjacent town to the south - to warrant a field trip. Four sites, all of which can be visited in the same day, are pinpointed herein. Some aspects of the geology of the area, plus minerals and rocks - including both the State Mineral and State Rock of Rhode Island - which can be found, are mentioned.

Much of this area matches the Pawtucket Quadrangle, for which a good geological map (Quinn et al., 1948) is also available. For the whole state, there is a more up-to-date map which can be obtained (Quinn, 1971).

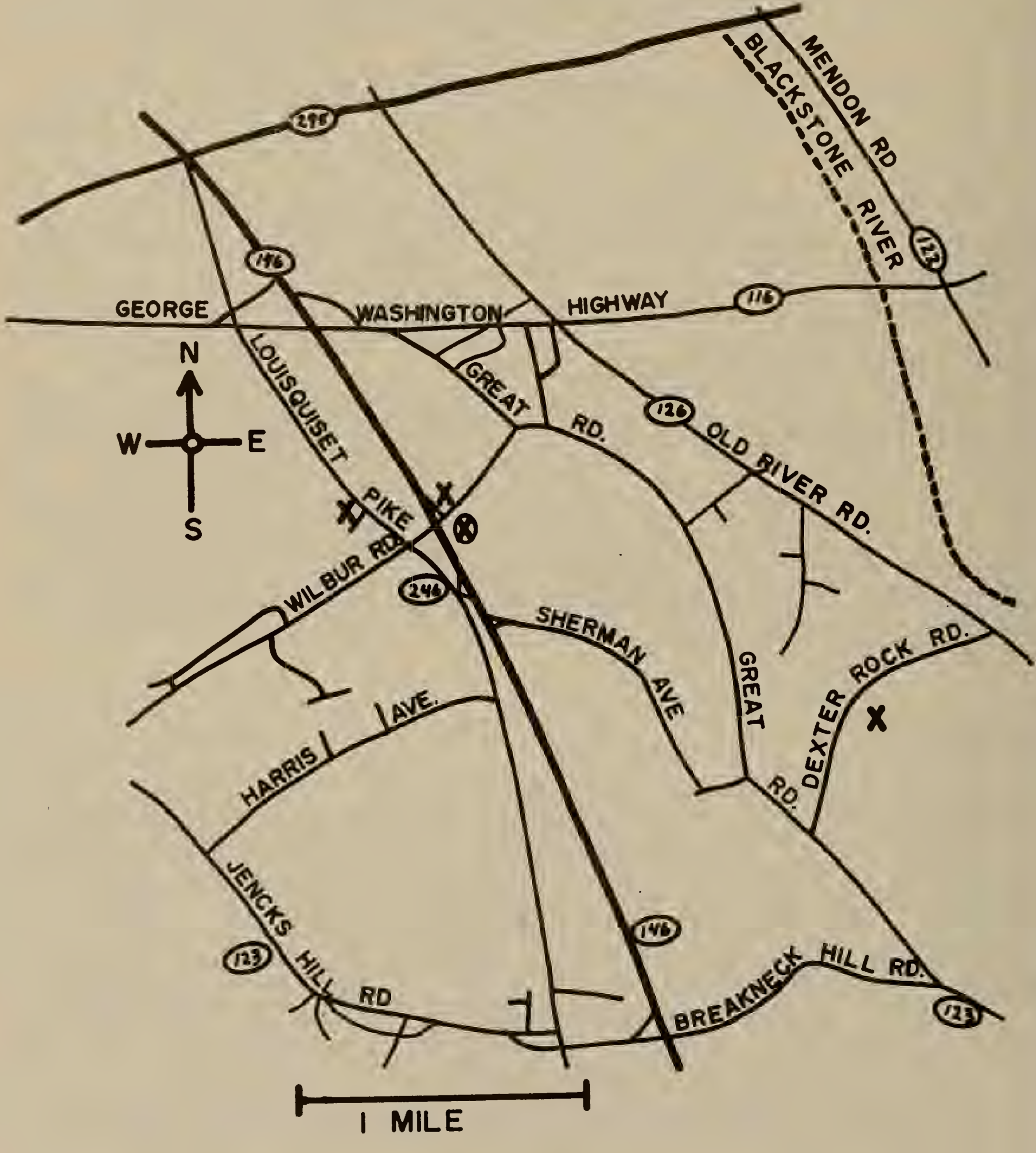
A dominant feature of this area is a presumed fault line running from north to south (roughly from Diamond Hill towards Valley Falls). To the east of the line, the bedrock is mostly sedimentary rocks (conglomerate, sandstone and shales) possibly of Pennsylvanian age some of which have been feebly metamorphosed . To the west there is a mixture of very old (Precambrian?) igneous and metamorphic rocks.

Driving directions to the four mineral sites are given in the Appendix.

Limerock

At the point (see circled cross on the map) where Route 146 and Wilbur Road cross is the Conklin Limestone Quarry, the last active source of limerock in the state. The rock being quarried, part of the metamorphic Blackstone Series (believed to be Precambrian in age), is a white to greenish-gray or light blue with some darker streaks, fine-to-medium grained stone. The bed of marble in this area is about 100 yards deep and extends from the quarry towards the northwest about half a mile (in which direction there are two inactive quarry sites shown by crosses). The overburden in the Limerock region is made up of glacial debris plus bedrock of metamorphic material from the Mussey Brook Schist and Hunting Hill Greenstone. The marble of the quarry is cut by several dikes of mafic rock (possibly olivine diabase).

The Conklin Linestone Quarry, (formerly the Harris), is one of the few active quarries in Rhode Island. It is also one of the few permanent mineral collecting areas in the state. Ed Conklin, the owner, does allow mineral hunters to collect here. The limerock is recrystallized limestone, technically marble because the area has been metamorphosed. It is dolomitic, having about 40% magnesium so the formula is near $CaMg(CO_3)_2$. Also there is minor amount (a few percent) of silica.


MENDON RD
BLACKSTONE RIVER
295
122
146
GEORGE
WASHINGTON
HIGHWAY
116
N
W
E
S
LOUISQUISET
PIKE
GREAT
RD.
126
OLD RIVER RD.
WILBUR RD.
246
SHERMAN
AVE
GREAT
RD.
DEXTER ROCK RD.
X
HARRIS
AVE.
JENCKS
HILL
RD
123
146
BREAKNECK
HILL RD.
123
1 MILE

Being a working quarry, one must go there a number of times in order to acquire a suite of minerals that are fully representative of the geologic environment; there is a regular turnover as the rock is continually being mined and taken away. There are about 40 species of minerals that have been collected from the Conklin Quarry or about 50 minerals including varieties. This is indeed a favorite area of mineral hunters with specimens being found in overburden, rock piles, and the quarry pit.

The most notable mineral obtainable here is Bowenite, the State Mineral of Rhode Island. Bowenite is a gemmy translucent variety of massive serpentine, possibly the antigorite polytype, of formula $(Mg, Fe)_3Si_2O_5(OH)_4$. The predominant color is an apple or yellow-green hue. It also exists in brown, pink or blue colors, and occasional colorless. It is usually admixed with the limerock and can have talc flakes or magnesite present. A vein of Bowenite exitsts in the north-central area of the quarry, and as deeper excavating is accomplished, more Bowenite becomes available. It has a very fine structure and will take a good polish. Thus it can be worked into a beautiful gem.

Table I is a list of minerals that have been collected at the Conklin Quarry, along with their formulae. Only the more prevalent or important minerals will be further expounded upon.

Several crystal forms of calcite have been found at Conklin, including rhombohedral, scalenohedral and nail head forms. Nail head crystals occur as overgrowths on top of scalenonhedral forms, which in turn appear as dog tooth crystals and thin wafer-line forms. The rhombohedrons are smallish, squatty crystals. The calcite crystals are generally colorless or grayish.

In the past calcite crystals have been collected from the southern part of the quarry. Other types of calcite specimens are crystals enclosing dendrites and crystals with quartz crystal growth on top. An exciting find was drusy quartz crystals over massive fluorescent calcite.

Many of the calcite crystals fluoresce a beautiful rose color. The limerock (colorless and white, bluish, brown or green) shows a yellow to blue fluorescence. However, this fluorescence gradually lessen with time and exposure.

Next to calcite, iron minerals are the most common occurance here. Black or reddish-brown goethite is found as botryoidal masses plus films and sometimes exhibits beautiful iridescent colors. Goethite has been collected on the top level to the east. Limonite geodes which contain sparkling druzy quartz crystals coating black or brown goethite have been obtained on the top level at the west side of the pit. Limonite matrices with colorless quartz crystals "coating" red-brown or black goethite forming little "trees" make for beautiful specimens, especially under the microscope. Other attractive micromounts are white-coated calcite crystals on drusy quartz which cover black goethite; this makes for a beautiful contrast under the microscope.

Hematite has been found in specular form as well as encrusting forms. The most unusual iron mineral collected here in the past is reddish-brown to silvery flake-like lepidocrocite exhibiting a pretty picture under the microscope.

Several varieties of quartz in combination with calcite or goethite have been mentioned. Quartz as rock crystal is fairly common. The writer (RLC) does have a citrine specimen from the Conklin Quarry. Some of the quartz crystals are stained brownish-yellow and also light blue chalcedony on chert is an exciting find at Conklin. Probably the predominant variety of quartz at

Table I

Minerals Found at Conklin Limestone Quarry

Mineral	Formula and/or Description	Mineral	Formula and/or Description
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)$	Epidote	$Cu_2(Al,Fe)_3Si_3O_{12}(OH)$
Adularia	$KAlSi_3O_8$-(orthoclase)	Essonite	$Ca(Al_2Si_6O_{10})\cdot 5H_2O$-(garnet)
Almandine	$Fe_3Al_2(SiO_4)_3$-(garnet)	Fosterite	Mg_2SiO_2
Anatase	TiO_2	Galena	PbS
Albite	$Na(Al,Si)(ALSi_2O_8)$	Goethite	$FeO(OH)$
Antigonite	$(Mg,Fe)_3Si_2O_5(OH)$-(serpentine)	Graphite	C
Aragonite	$CaCO_3$	Hematite	Fe_2O_3
Asbestos	$Mg_6(Si_4O_{10})(OH)_8$-(Chrysotile)	Hornblende	$Na,Ca_2(Mg,Fe,Al)_5(OH)_2(Si,Al)_8O_{22}$
Bornite	Cu_5FeS_4	Hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot 4H_2O$
Bowenite	"Gem" Serpentine	Ilmenite	$FeTiO_3$
Calcite	$CaCO_3$	Kaolinite	$Al_2Si_2O_5(OH)_4$-(clay)
Chlorite	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	Lepidochrocite	$FeO(OH)$
Chryscolla	$Cu_2H_2Si_2O_5(OH)_4$	Limonite	$FeO(OH):nH_2O$
Chert	SiO_2-(Quartz)	Magnesite	$MgCO_3$
Citrine	SiO_2-(Quartz)	Magnetite	$FeO\cdot Fe_2O_3$
Dendrites	MnO_2-(pyrolusite)	Malachite	$Cu_2(CO_3)(OH)_2$
Dolomite	$CaMg(CO_3)_2$	Microcline	$KAlSi_3O_8$-(feldspar)

Mineral	Formula and/or Description
Molybdenite	MoS_2
Montmorillonite	$(Al,Mg)_8(Si_4O_{10})_3(OH)_{12}\cdot$ 12 H_2O-(clay)
Muscovite	$KAl_2(Al,Si_3)O_{10}(OH)_2$-(mica)
Pyrite	FeS_2
Pyrolusite	MnO_2
Quartz	SiO_2 (crystals)
Quartz	Chalcedony
Quartz	Hyalite Opal
Rhodochrosite	$MnCO_3$
Rhodonite	$(Mn,Fe,Mg)SiO_3$
Rutile	TiO_2
Scheelite	$CaWO_4$
Scolecite	$Ca(Al_2Si_3)O_{10}\cdot 3H_2O$
Siderite	$FeCO_3$
Talc	$Mg_3Si_4O_{10}(OH)_2$
Tourmaline	$WX_3Y_6(BO_3)_3Si_6O_{18}(OH,F)_4$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_{12}$
Wad	$MnO_2\cdot nH_2O$
Zoisite	$Ca_2Al_3(SiO_4)_3OH$
Marble	$CaCO_3$-(a rock)
Limestone	$CaCO_3$-(a rock)

the quarry is chert, usually of brown color and occasionally of polishable grade.

There are several other minerals of interest. In the contact zone of limerock and the greenstone, schorl, the black variety of tourmaline, has been found; schorl is also associated in small pegmatite veins with mica and quartz. Typical adularia crystals occur with quartz and sometimes with malachite also. Specimens of limerock with lovely pink montmorillionite coating have been collected.

In conclusion while the minerals collected at Conklin Quarry are not spectacular, except for some specimens when viewed under the microscope, they certainly are of "beauty" and interest to the geologist and the serious mineral collector. The minerals that attract the most attention are bowenite, goethite in various forms, chalcedony, chert and crystals of calcite. The lepidocrocite specimens stand out as interesting and unusually beautiful forms of an iron mineral.

Old Dexter Quarry Kiln

About 0.3 mile SE from Conklin on Wilbur Road to Great Road, go right 1.6 miles on Great Road to Dexter Rock Road, go left 0.8 mile on Dexter. Near the first house on the right are the remains of an old kiln. The quarry (shown as a cross on the map) is filled and now used as a dump. Beautiful rhombohedral calcite crystals of yellowish cast have been collected here. The yellow color is caused by limonite precipitation on the calcite. Sericite mica and also very small prismatic needles of scolecite (a zeolite) have been taken (dried out) on the kiln sides. Unusual quartz crystals also were obtained before the quarry was filled.

Diamond Hill

Well to the north of the quarry and just to the east of Route 114 is a considerable mound (1000 feet wide and mile long) of vein quartz. The west bluff of this mount (known as Diamond Hill presumably because of the quartz crystals) which is south of the ski trail area shows particularly clearly from a distance.

Quinn et al. (1949) have suggested that this quartz probably was deposited by hot waters moving along a fault between the Pennsylvanian rocks to the east and the older rocks on the west. The quartz is more resistant to erosion than the surrounding rock and this is the presumed reason that Diamond Hill stands out above the nearby terrain.

The rock is primarily milky quartz with numerous vugs (some having fair crystals); also present are agate and jasper (a little of which is polishing quality) plus iron oxides (hematite, goethite and limonite - at one time abundant enough to be mined).

Route 114 Roadcut

About 200 yards west of the juntion of state routes 121 and 114 on the north side of the latter road is a large roadcut having an unusual array of minerals. The bedrock is primarily Quincy Granite, a gray medium-grained massive rock. Cutting the granite are many veins of quartz and of blackish rock with metallic sheen. Also there is some granite gneiss with considerable hornblende.

This site is where crystals of the rare mineral danalite (or one of its isostructual relatives) have been found, even as recently as early 1981. The prettiest specimens are light pink tetrahedra. Other minerals obtained from this cut include ankerite, fluorite, sphalerite, apatite and pennenite among others. The Quincy Granite has finely-divided riebeckite and aegirite besides quartz, microperthite and biotite; chemical analysis indicates that this rock fits the modern classification scheme as an Alkaline Feldspar Granite.

Iron Mine Hill

Close to the southwest corner of West Wrentham Road and Elder Ballou Meeting House Road can be found the remnants of a once-active quarry of cumberlandite. This peculiar igneous rock has been disignated the state rock of Rhode Island.

Cumberlandite is very dense and weakly magnetic. While most often black, exposed surfaces tend to be brownish. It is principally made up of magnetite and ilmenite in an intimate fine-to-medium-grained mixture, along with some olivine, labradorite and spinel. The feldspar stands out as white to greenish crystals up to half an inch long. On well weathered specimens, this component weathers relatively rapidly and leaves a surface with pits of characteristic shape.

Cumberlandite, because of its unusual nature and single source, presents the possibility of tracing the path(s) of the glaciers that passed over Rhode Island. Remnant cumberlandite stones have been found in an area which roughly follows Narragansett Bay fanning out as the boulder train proceeded southward. One of us (JOE) has found cumberlandite stones in Providence, East Providence, Block Island and Little Compton; a sufficient number were found in the moraines at Little Compton to indicate that Quinn's (1976) portrayl of the "boulder train" does not reach far enough to the east side of Narragansett Bay. Specimens in the Roger Williams Park Museum collection include some from Cranston, Prudence Island, Johnston, Warwick Neck, Pawtucket and Bristol. Quinn (1976) reports that some of this rock has been found on Martha's Vineyard. As would be expected, these well-traveled pieces of cumberlandite are usually found in morainal locations. Black magnetic sand, in all probability from glacier grinding of cumberlandite, has been collected on beaches at Warren and Block Island.

Other nearby sites

A large number of minerals have been found in the townships of Cumberland and Lincoln. Miller (1971) lists 140 and 84 reported minerals and varieties respectively from these two towns. Some of the more unusual finds include astrophyllite, sagenetic quartz, molybdenite and cecilite (an ore of uranium, thorium, rare earths and noble metals).

Directions to some of the locations can be obtained from the authors. Additional references that might prove useful to the mineral collector are listed in the reference section.

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APPENDIX

Directions to Mineral Sites

An excellent free road map of Rhode Island may be obtained from the Department of Ecomonics Department, 7 Jackson Walkway, Providence, R.I. 02903.

I. To the Conklin Quarry (at Limerock, Rhode Island)

A. From the south, go north on Route 146 to the Sherman Avenue Exit. Follow Sherman, Great Road and then Wilbur Road (keeping to the left at intersections) until almost back to 146. The quarry will be on your left.

B. From the north, depart from Route 146 south at exit labeled Route 246. Double back over this parallel road about 200 yards, cross over Rt. 146, and the quarry will be directly on your right.

II. To Diamond Hill

A. From Conklin Quarry take Route 146 north to Interstate 295 (3 km). Go east on 295 to R.I. 114 (6 km), and proceed north on 114 about 5 km. There are places to pull cars off the road near the very visible west face of Diamond Hill. This is about 0.5 km south of the main parking lot of the State Park.

B. Unless you are familiar with the area, the more satisfactory way to go to Diamond Hill is by way of Interstate 295 and R.I. 114.

III. To the Route 114 Roadcut

Proceed on 114 north from the west face of Diamond Hill (about 1 km) to the junction of routes 121 and 114. Turn left with 114 (which here goes west) and travel about 200 miles to the large road cut on the north side of the road. Cars can be pulled over to the shoulder of the road.

IV. To Iron Mine Hill

A. From the route 114 raoadcut, proceed west about 2 km to West Wrentham Road. Turn south on this road and proceed less than 1 km to Elder Ballou Meeting House Road. About 100 meters on the left of this road, there is room for a couple of cars to pull off. The old quarry is about 100 100 miles to the south.

B. The quarry can also be reached from the south. State Route 122 (Mendon Road) connects (in the village of Cumberland Hill) with the south terminus of West Wrentham Road.

SEDIMENTATION IN MICROTIDAL COASTAL LAGOONS,

SOUTHERN RHODE ISLAND

Nancy Friedrich[1], Stephen R. McGinn[1], and Jon C. Boothroyd[1]

INTRODUCTION

The Charlestown barrier spit-lagoon complex is centrally located on the southern Rhode Island coast (Fig. 1). The barrier spit is 6 km long E-W, varies in width from 200 to 400 meters, and serves to separate the back-barrier lagoon from Block Island Sound to the south. This coastline is classified as a mixed energy, wave-dominated coast after Hayes (1980) (Fig. 2). Local relative sea-level rise is proceeding at a rate of 30 cm per 100 years (Hicks, 1974).

The barrier spit includes a narrow beach, a low dune ridge, vegetated back-barrier flats, and a stabilized inlet (Fig. 3). Subenvironments within the back-barrier lagoon (Fig. 4) include washover lobes to the west of the inlet, flood-tidal delta deposits north of the inlet, a low-energy lagoonal basin, and erosional terraces along the near margins of the lagoon.

STOP 1. Charlestown Breachway and Flood-Tidal Delta

Two stone jetties have been used to stabilize the Charlestown Breachway. Construction was begun in 1952 and completed in 1954 (Lee, 1980). The breachway is oriented N-S, is 33 meters wide, and 1.6 meters deep. Spring tide range (16 August 1979) within the breach is 80 cm, the maximum surface flow velocity was 170 cm sec^{-1}. Flow through the breach is flood dominant. The inlet throat widens at the termination of the jetties and a small flood-tidal delta is present in the main channel.

The main channel bifurcates around Wards Island with the greatest volume of water proceeding north over the west lobe of the flood-tidal delta (Fig. 5).

Four vibracores were taken along a transect through this area (Fig. 4). Three cores were taken from the east lobe and one in the lagoon to the north. A cross-section constructed from core logs (Fig. 6) shows glaciofluvial deposits overlain by fresh-water wetland peat succeeded by a marine lagoon sequence. The lagoon sequence begins with erosional terrace/beach deposits followed by low-energy lagoon organic silt. Distribution of these deposits is controlled by the underlying Pleistocene topography and they are not always present in all cores. Flood-tidal sands are deposited over the finer grained basin sediments.

A sedimentation rate of 6.9 ± 1.4 cm yr^{-1} has been established for the flood-tidal area through the use of Pb-210 dating (Fig. 7). See Figure 4 for sampling location.

From 1951-1980 the flood-tidal delta grew by 141683 m^3 (Fig. 8). Sixty-one percent (87091 m^3) of this accretion occurred between 1951 and 1963, twenty-eight percent (39500 m^3) occurred between 1963 and 1972, while only eleven percent

[1] Department of Geology, University of Rhode Island, Kingston, RI 02881

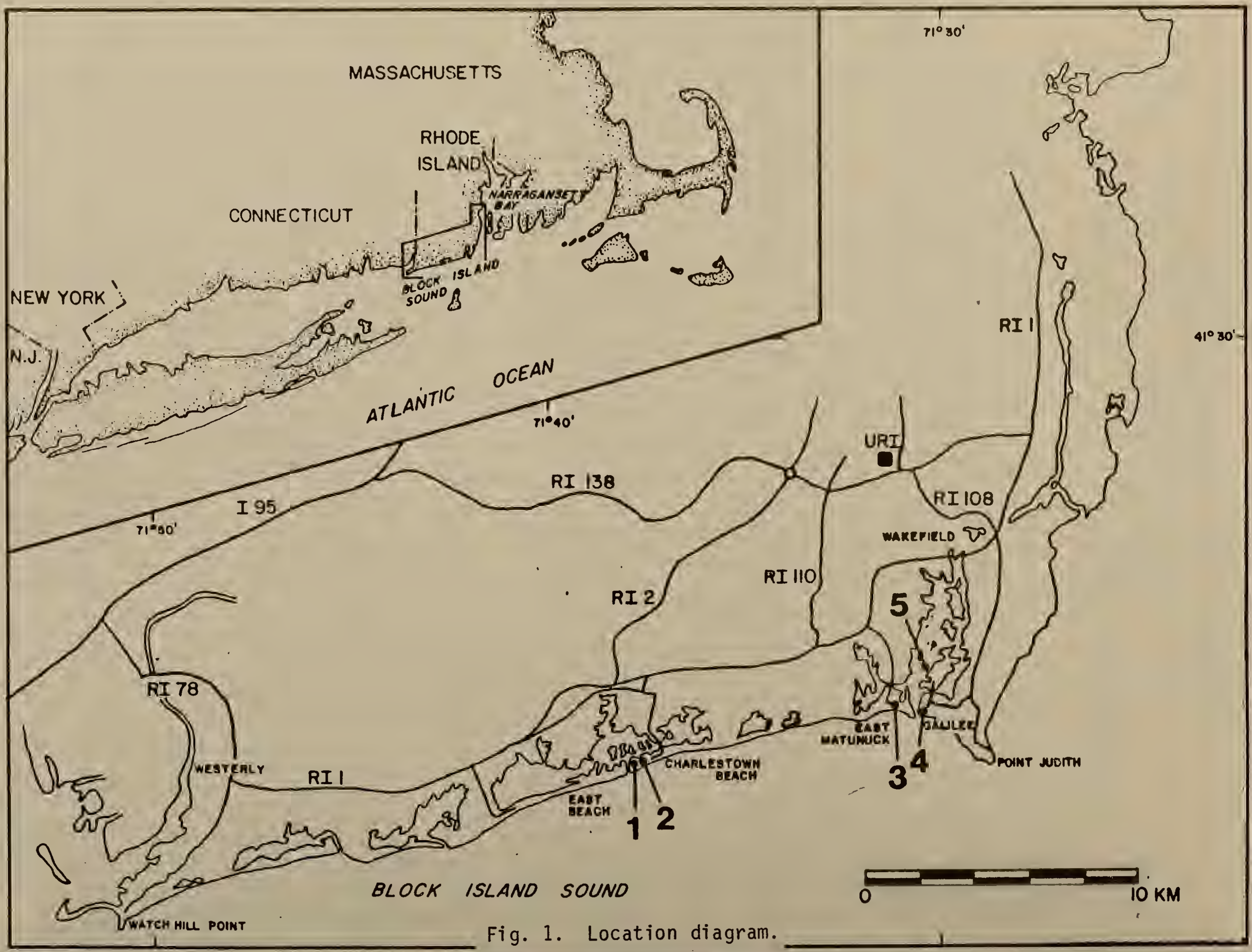

Fig. 1. Location diagram.

Fig. 2. The Ninigret Pond flood-tidal delta and adjacent barrier spits. B - Charlestown Breachway, CB - Charlestown Beach, D - dredge channel, E - East Lobe of flood-tidal delta, EB - East Beach, EC - East Main Channel, G - Green Hill Bridge, M - Main Channel, W - West Lobe of flood-tidal delta, WI- Wards Island, 1 - Stop 1, 2 - Stop 2, site of the CHA-EZ profile. The low-energy basins of the lagoon are in the top of the photo. This photo is a low oblique looking north, taken on 28 June 1981.

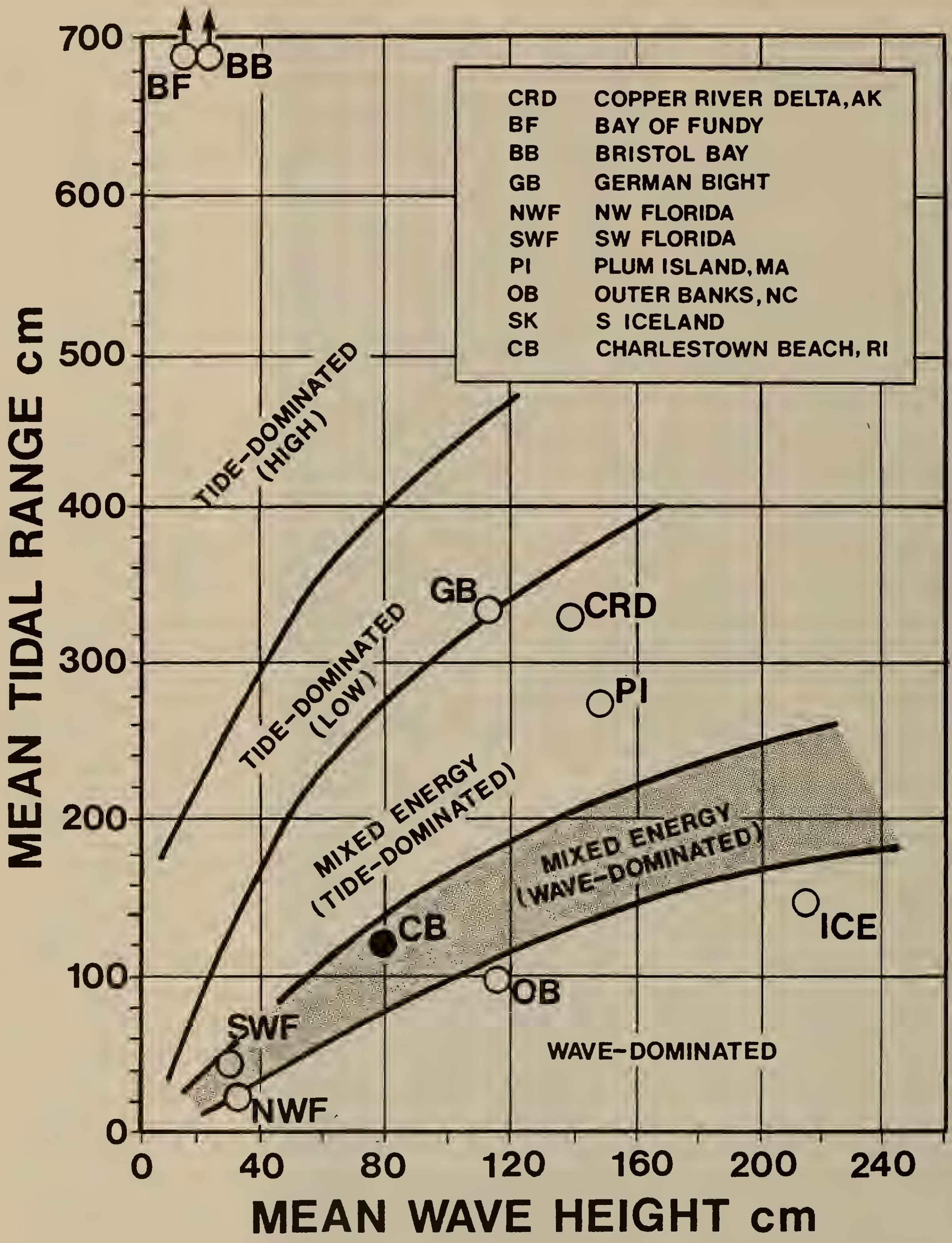

Fig. 3. A plot of wave height versus tidal range. The Rhode Island coastline is indicated by the filled circle and is labelled CB. From Hayes (1979), Charlestown wave data from Swanson (written communication, 1980).

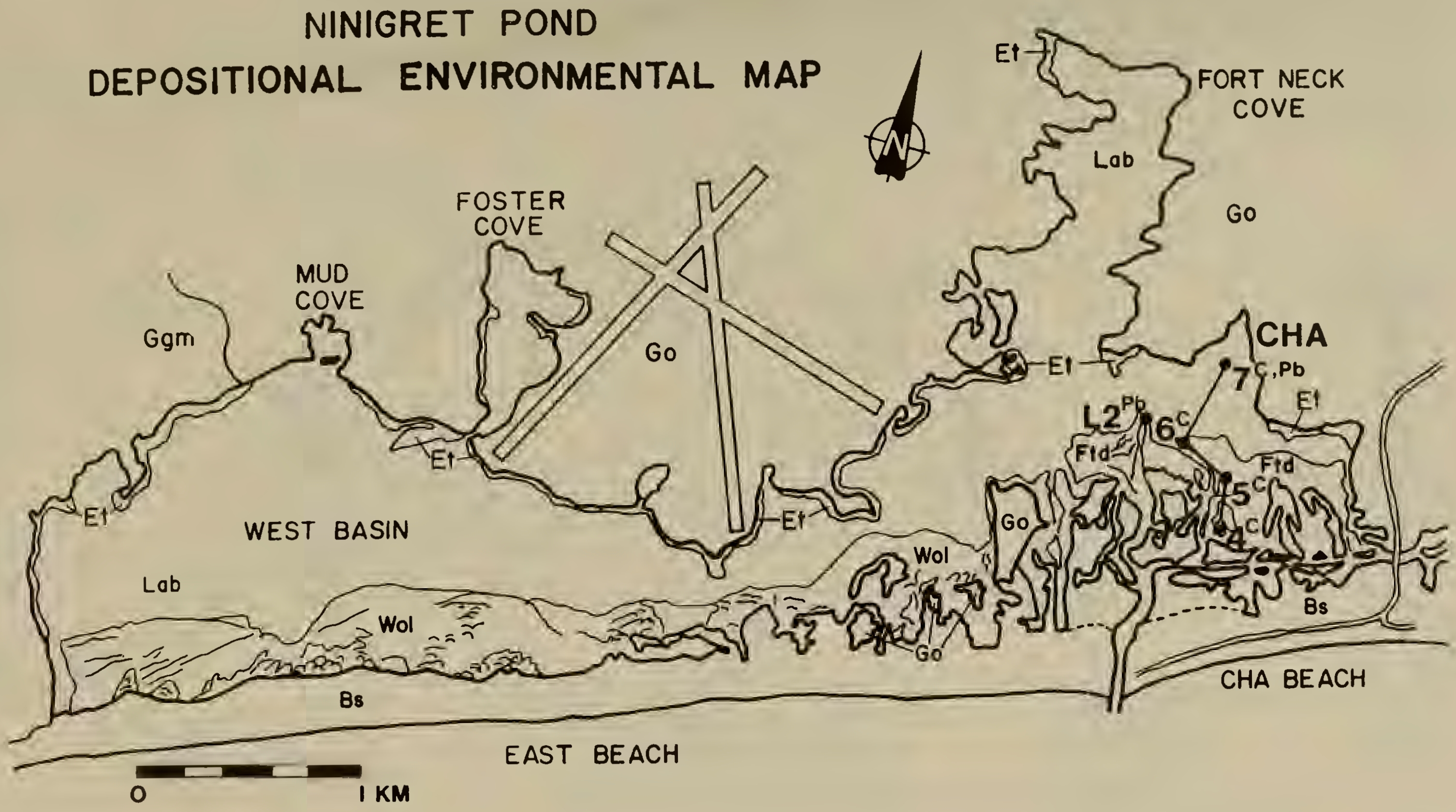

Fig. 4. Simplified depositional environmental map with vibracore and radiometric dating locations. Large letters (CHA) designate core transect, numbers along the transect identify core locations. Small letters (C, Pb) indicate C-14 or Pb-210 dating sites. The geologic units are Bs - barrier spit, Ftd - flood-tidal delta, Wol - washover lobe, Lab - lagoon basin, Et - erosional terrace, Go - glacial outwash, and Ggm - glacial ground moraine.

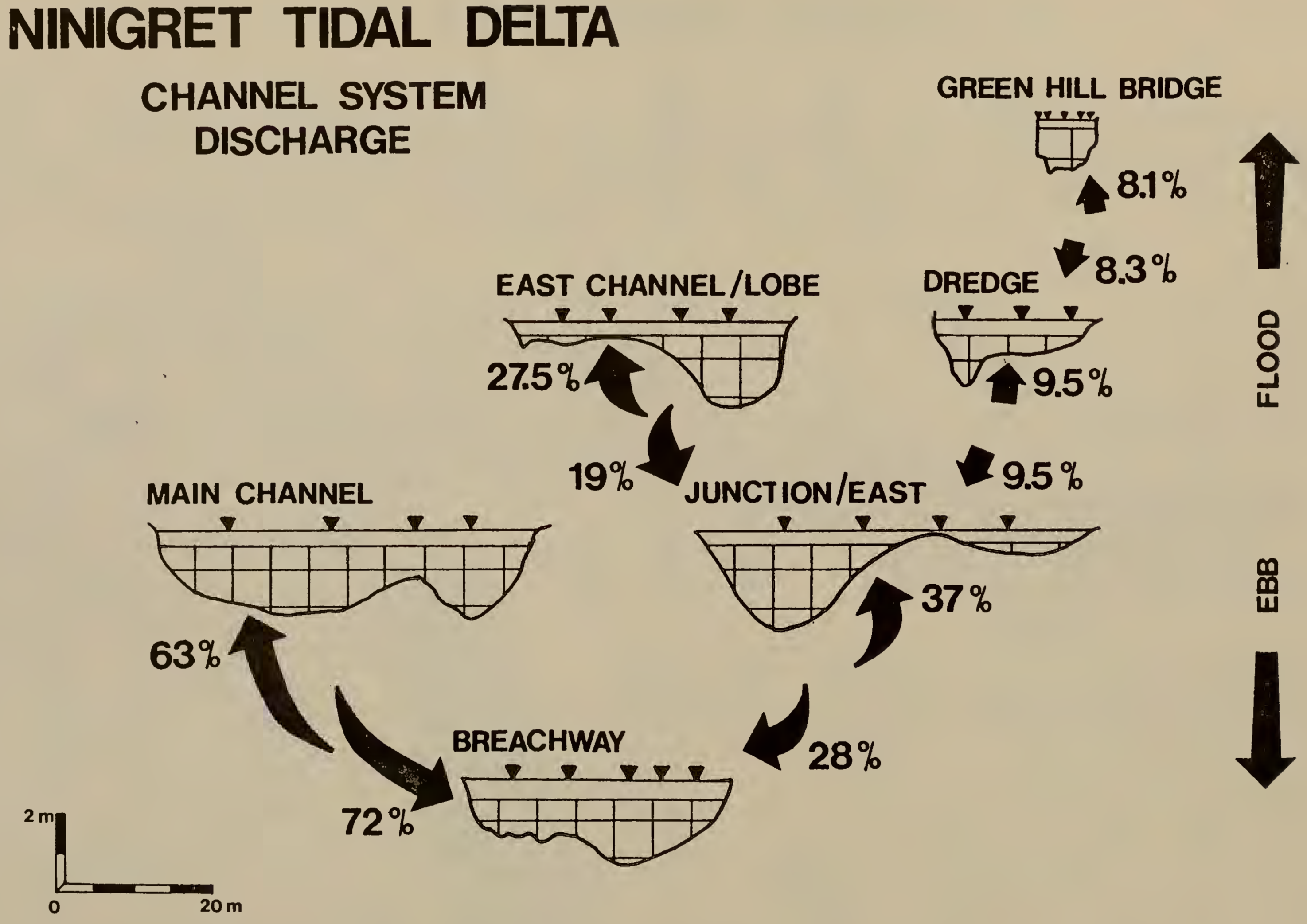

Fig. 5. Schematic diagram indicating percentage of total discharge that each channel carries on the flood and ebb.

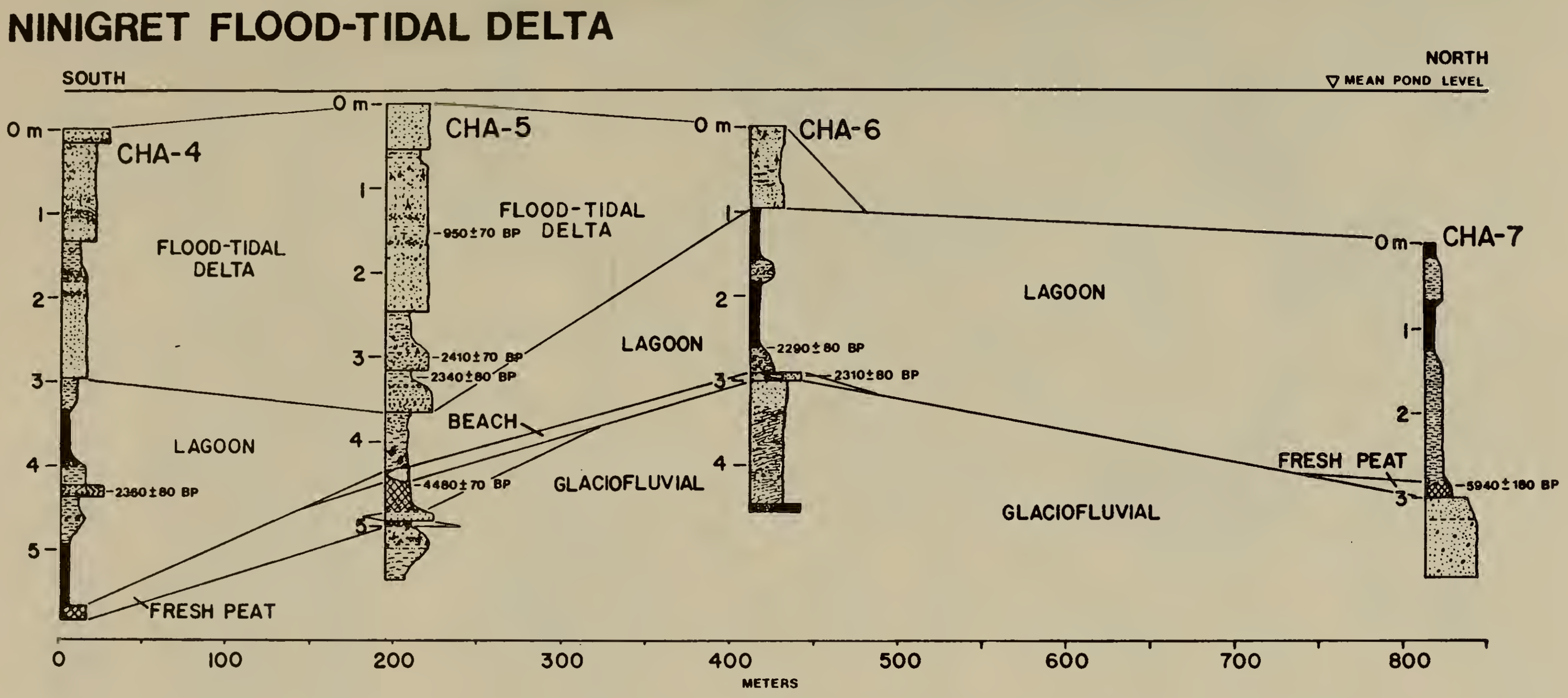

Fig. 6. Flood-tidal delta transect, Ninigret Pond. See Figure 3 for locations. Grain size is shown by width of log, narrow for silt to wide for gravel; internal stratification, shells, and roots also shown. Ages were obtained from C-14 dating of shells, peat and wood.

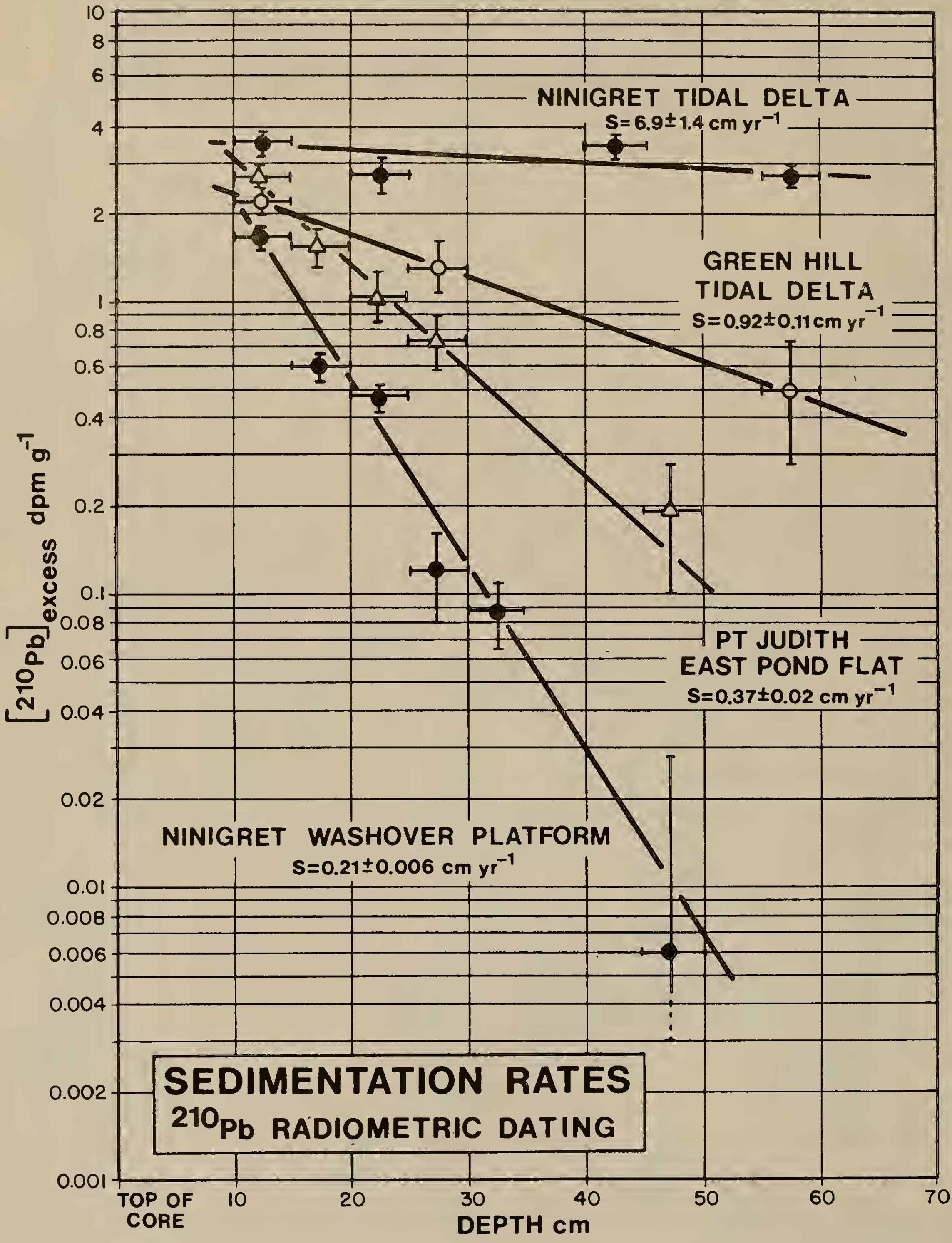

Fig. 7. Sediment accumulation rates obtained by Pb-210 dating of organic material in cores. Sampling location for Ninigret Pond is shown in Figure 3 ($L2^p$).

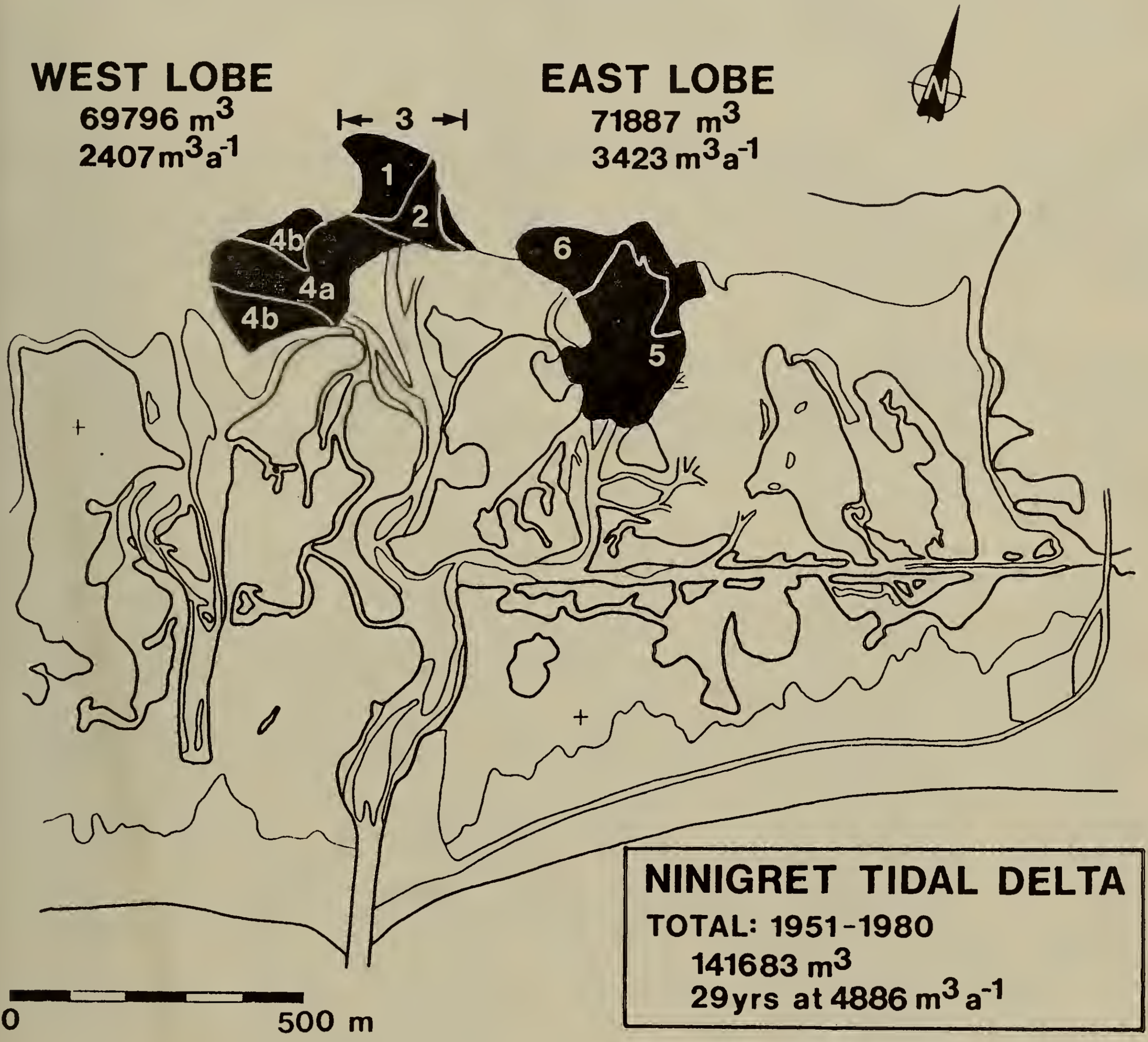

Fig. 8. Growth of flood-tidal delta lobes, Ninigret Pond. Areal change through time was determined by measuring intertidal and subtidal flats on sequential vertical aerial photographs (1951, 1963, 1972, 1975, 1980). A sediment thickness of 1.0 and 1.3 m, based on stratigraphy in vibracores, was used to compute sediment volumes. Numbers refer to times of accretion as follows: 1) 1975-1980, 2) 1972-1975, 3) 1972-1980 (composite), 4a) 1951-1963, 4b) 1963-1972, 5) 1951-1963, and 6) 1963-1972. See text for volumes. From Boothroyd et al (1981).

(15093 m^3) occurred between 1972 and 1980. Examination of aerial photographs show negligible areal changes in the flood-tidal delta from 1938 to 1951 so that the probable cause of flood-tidal delta growth is the opening of the permanent breachway in 1952-1954.

STOP 2. Profile CHA-EZ

Beach profiles, using the Emery method, have been taken at this locality every 1-10 days since 1 October 1977 (Fig. 9). A computer is used to plot the profile and to calculate the area under the curve. Profile volumes are reported as cubic meters per linear meter of beach. Two contrasting profiles, illustrating a mature beach profile and a post-storm profile, are shown in Figures 10a and 10b.

Change in the total profile volume (Fig. 9) is a combination of berm erosion and recovery and foredune ridge erosion. Small net change in the total volume indidates that some of the eroded dune material is incorporated into the berm during recovery. There is a strong correlation between berm volume changes and storm/fair weather cycles. A minor seasonal fluctuation is also observed (Boothroyd and O'Brien, 1980).

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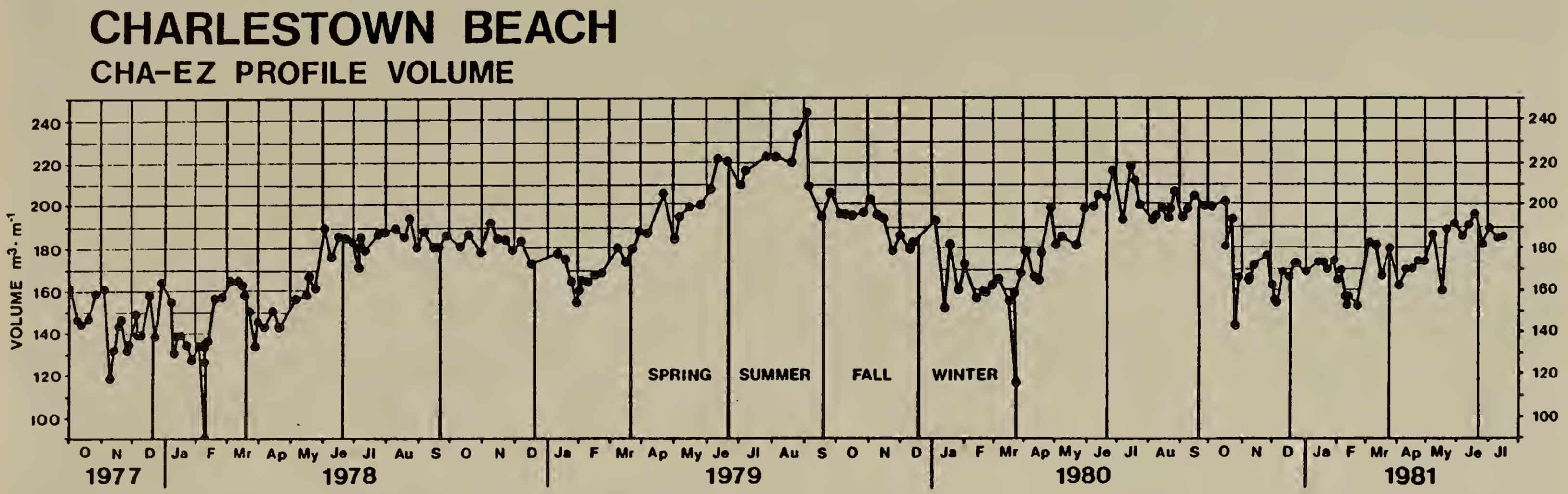

Fig. 9. Plot of CHA-EZ profile volume through time. Profile volumes are reported as cubic meters per linear meter of beach. Two on-site weather recording stations are used to monitor wind speed, wind direction, barometric pressure, temperature and humidity. A hand held anemometer is also used to measure wind velocities on the beach during profiles. Wave height and approach directions are determined along with longshore drift direction and speed. A consideration of profile volumes, coupled with the on-site weather and wave data, will lead to a better understanding of local coastal process-response mechanisms.

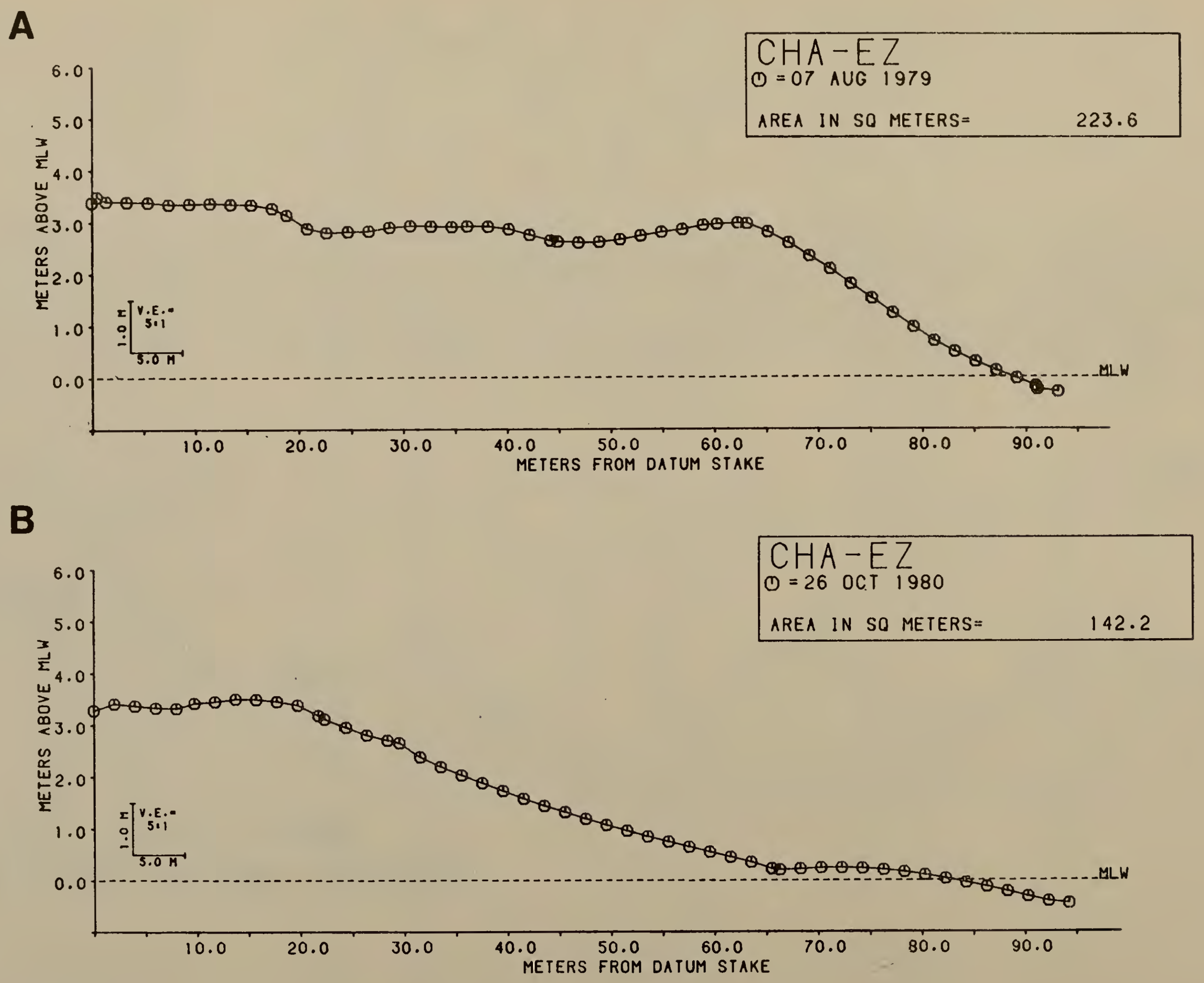

Fig. 10. Computer plotted profiles for the CHA-EZ location. A) Mature profile - exhibits a large berm, steeply sloping beach face, gently landward dipping berm top, and a poorly-to-well-developed seaward dipping face landward of the berm top. B) Post-storm profile - a flat beach with a pronounced intertidal to subtidal bulge of sand. The swash bar is quickly returned to rebuild the berm and recovery is rapid.

Fig. 11. Lower Point Judith Pond and Succotash Marsh. B - Point Judith Breachway, EM - East Matunuck State Beach, G - Great Island, J - Jerusalem, P - Potter Pond, PJ - Point Judith Pond, S - Succotash Marsh, 3 - Stop 3, 5 - Stop 5, an intertidal flat. The docks of Galilee can be seen in the right of the photo (Stop 4). This photo is a low oblique looking north, taken on 28 June 1981.

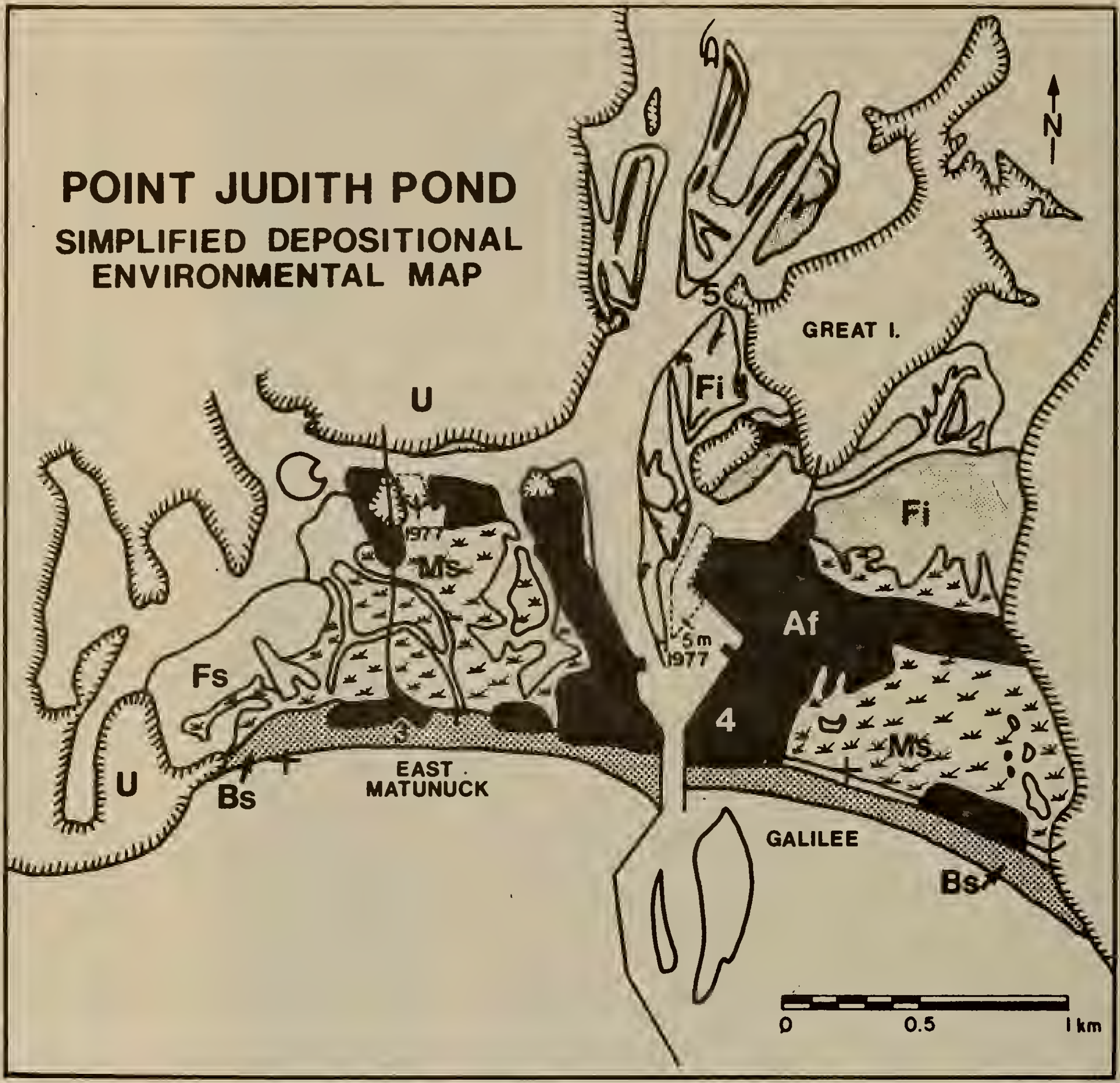

Fig. 12. Lower Point Judith Pond and Succotash Marsh, simplified depositional-environmental map. Numbers refer to stop locations. Geologic units: Af - artificial fill, Bs - barrier spit, Ms - marsh, U - glacial upland, Fi - intertidal flats, Fs - subtidal flats.

Itinerary

The field trip will leave from the Keaney parking lot beside the athletic fields, University of Rhode Island. It involves walking in water, wet sand and mud. A small boat will be used to gain access to two stops. Wear hip waders, sneakers, or tennis shoes. Do not wear field or hiking boots.

Distance (In Miles) Pt. to Pt.	Total	Route and Stops
0	0	Leave Keaney parking lot, turn right (west) on RI 138.
0.6	0.6	Intersection of RI 110 at lights. Turn left (south) on RI 110. This route is also called Ministerial Road.
3.8	4.4	Tuckertown Four Corners, intersection of Wordens Pond Road on the right (west), and Tuckertown Road on the left (east), located on ice-contact deposits just north of the Charlestown end moraine. Proceed south through the intersection and up onto the moraine.
0.7	5.1	Backside (ice-contact slope) of Charlestown moraine.
1.3	6.4	Intersection with Old Post Road, and beginning of proximal outwash plain. Proceed south to US 1.
0.2	6.6	US 1, go west past exits to Moonstone and Green Hill beaches. Charlestown moraine on the right.
1.2	7.8	Charlestown Beach exit; Exit from left lane onto US 1, north.
0.3	8.1	Exit right at Charlestown Beach breachway sign. Proceed 100 yds. to stop sign (intersection with US 1A); continue straight through stop sign. Pass over proximal outwash plain (former potato farm).
0.5	8.6	Turn left at stop sign onto Schoolhouse Rd; follow Beach/Breachway signs.
0.1	8.7	Turn right onto Charlestown Beach Rd. Proceed south on the outwash plain; across a small till upland, and down to the lagoon.
1.3	10.0	Green Hill Pond bridge; Charlestown Pond with dredged channel to the right; Green Hill Pond

		to the left (small island with house is a till upland). Beyond the pond is Green Hill, a drumlin.
		Bear left off bridge onto back barrier. Proceed 200 yds.
0.2	10.2	Bear right to travel west along the back barrier. Example of a developed barrier spit, most houses built since 1970.
0.5	10.7	Location of CHA-EZ profile.
0.1	10.8	Two houses formerly on left lost in 1977-78; area of active overwash.
0.1	10.9	Charlestown Breachway (State Camping Area), gravel parking lot.
		STOP 1. This will be a long stop to view the breachway jetties constructed in 1952, and then walk north (lagoonward on flood-tidal delta deposits. 200 m north is a straight, manmade channel dredged in 1962 to Green Hill Pond. Embark in boats for a short cruise to the tidal-delta flats. Note the channel point bars, channel-margin flats, flood ramp, and high marsh.
		Leave breachway parking lot, heading east along back barrier.
0.2	11.1	Location of CHA-EZ beach profile.
		STOP 2. The beach profile has been run at 1-10 day intervals since Oct, 1977. Severe erosion occurred during 1977-78; no dune recession has been recorded since Feb. 1978 (as of early Aug. 1981). The houses are on piling with floor joints set at the 1938 hurricane storm-surge still water level.
0.7	11.8	Return east along back barrier to the Green Hill Pond bridge. Proceed north.
1.3	13.1	Intersection Charlestown Beach Rd. and Schoolhouse Rd. Turn left at Stop sign onto Schoolhouse Rd.
		Proceed 200 yds.; turn right, heading north.
0.5	13.6	Stop sign; intersection with US 1A. Continue straight.
0.1	13.7	Bear right onto US 1 (north). Drive east and north along the front slope of the Charlestown moraine, past exits for Moonstone and Matunuck beaches.

		Proceed up onto the moraine with a view of Potter Pond on the right.
5.1	18.8	Exit right off US 1 north at the Jerusalem, Snug Harbor, East Matunuck State Beach sign. Proceed south on Succotash Rd.
0.6	19.4	Bear right at fork.
0.7	21.1	Potter Pond bridge: Succotash Marsh on left; Potter Pond right; houses built on glacial upland and areas of dredge spoil.
0.6	21.7	Bear right into East Matunuck State Beach parking lot.
		<u>STOP 3.</u> The State Beach pavilion sits astride the location of the 1897 tidal inlet. We will walk west to the gravel washover fans on the spit fronting Potter Pond; then east onto Succotash Marsh, a marsh-covered flood tidal delta. The areas covered with shrubs are glacial "islands" poking through the tidal-delta deposits.
		Return north along Succotash Rd; over Potter Pond bridge to US 1.
1.9	23.6	Turn right onto US 1 (north).
3.0	26.6	Saugatucket River passes under the road to Pt. Judith Pond (on the right).
0.8	27.4	Exit right off US 1 at sign for Point Judith, Scarborough, and Galilee. Proceed up off-ramp; turn right onto Woodruff Ave; follow signs for Point Judith. Bear right at lights onto RI 108 (south).
		Drive south on RI 108 several miles, through to intersection with traffic lights. You are traversing along Pt. Judith end moraine.
4.2	31.6	Fisherman's Memorial State Park on right; the site of coastal defense gun batteries guarding the east entrance to Narragansett Bay during WW II.
0.1	31.7	Exit right off 108, onto the "Escape Route", heading west (road work begun in 1954 and finished in 1956).
0.7	32.4	Sand Hill Cove Marsh on left East Pond, part of Point Judith Pond on right.
0.5	32.9	Turn left (south) at T-intersection onto Great Island Rd. Entering Village of Galilee.

0.4	33.3	Turn right into parking lot next to breachway jetty.
		STOP 4. Pt. Judith breachway. An inlet formed naturally at this site in 1901 and was stabilized with jetties beginning in 1909. Tidal-current discharge is 6-8 times that of Ninigret Pond and periodic maintenance dredging is needed to remove the flood ramp and ebb spits, and maintain project depth over the developing bedforms.
		Turn right (east) out of parking lot.
0.1	33.4	Turn left at sign for Providence, and Great Island.
0.4	33.8	Turn right at Stop sign onto Great Island Rd (north). Proceed north to Great Island.
0.3	34.1	Great Island Bridge.
0.1	34.2	Bear left at blinking light onto Conch Rd.
0.2	34.4	Turn left onto Island Rd. (also sign for Mollusk Drive).
0.1	34.5	Bear right down private drive to small, sandy parking lot. STOP: private property; leave vehicle and walk to house on point; request permission to cross property.
		STOP 5. There is a good view at low tide from this island of glacial material. Visible are the mid-pond intertidal flat and bar systems. We will visit the largest flat, by boat, embarking from the boat launching area near the parking lot. Note the variety of fauna on the tidal flat.
		END OF TRIP

GLACIAL GEOLOGY OF SOUTHERN RHODE ISLAND

J.P. SCHAFER[1]

ITINERARY

STOP 1. The "University pit", north-northwest of University of Rhode Island, 0.25 mile north-northeast of 124 foot road intersection, in northeast part of Kingston quadrangle.

South Pit - This pit is in a broad outwash plain, and the southern part of the pit exposes flat undisturbed sand and pebble gravel with stream crossbedding. The outwash is mantled by the late-glacial windblown material, which shows late-glacial frost disturbance. The boulders encountered in the east edge of the pit may well be from till beneath the outwash, the buried continuation of the adjacent till hillside.

North Pit - This pit has usually provided the best exposures of late-glacial frost features in Rhode Island. The uncollapsed part of the outwash shows abundant involutions in the lower part of the eolian material and extending down into the top of the gravel. These involutions are approximately symmetrical in vertical section and equidimensional in horizontal section, and may easily be distinguished from load casts or from wind-throw structures. This part of the pit has produced about eight ice-wedge structures over the years. The wedges vary from about 1 to 2 feet wide at the top, and end at depths of 6 to 9 feet. They are known from very few localities, and as far as we can tell from their orientation, they occur only as separate structures, not as nets. The perennially frozen ground that they indicate might have been only thin and patchy.

In the southwest part of the pit, the outwash shows collapse structure related to the adjacent kettle. This kettle was partly filled with windblown material and gravel, redeposited from the adjacent slopes by local slopewash. Near the kettle, poor drainage conditions have produced unusual color effects through the action of groundwater, including local cementation by crusts of iron oxide.

EN ROUTE TO STOP 2.

We travel about 2000 feet north on the outwash plain, into the Slocum quadrangle.

STOP 2. Small moraine 0.5 mile east of Hundred Acre Pond, in southeast part of Slocum quadrangle.

Walk along road across this moraine, which stands at the head of the outwash plain of Stop 1 and was deposited at the edge of the ice from which the outwash rivers came. The moraine is a bouldery ridge, distinctly higher than the adjacent outwash. A small pit shows collapsed sand and gravel and a little till, with many boulders (one of which is strongly fluted by wind abrasion). The bed of the brook that descends the north or ice-contact face of the moraine contains a lag concentration of large boulders.

This moraine appears to be part of a thin line of morainic features rising out of the outwash in the north central and northwestern parts of the Kingston quadrangle.

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[1] U.S. Geological Survey, 928 National Center, Reston, Virginia 22092

On the Kingston quadrangle geologic map a long narrow ridge situated about 2 miles west-southwest from Stop 2 is labelled crevasse-filling. A mile or so further west, a belt of kamy hills cuts across the Usquepaug Valley. Plate 33 of the Kingston quadrangle report suggests an ice front responsible for this thin morainic belt. If these features are correctly interpreted, then the ice readvance or retreatal still-stand at this line was certainly a minor affair.

EN ROUTE TO STOP 3.

Road is on outwash plain that appears to head a small moraine that crosses the valley of the Chipuxet River in the Slocum quadrangle, just north of the Kingston quadrangle. South from Rte. 183, Ministerial Road crosses the deltaic front of this outwash plain where it built out into Glacial Lake Worden, a glacial lake dammed in part by the Charlestown moraine, which is to our south here. Most of the area of Glacial Lake Worden is now occupied by a large swamp, the Great Swamp, famous as the place where King Philip and his Indians were finally depeated by the colonists in 1675.

The road climbs a till-mantled rock knob, Tobey Neck, that arises from the swamp, and then crosses several patches of outwash gravel lying just north of the Charlestown moraine.

STOP 3. North side of Charlestown moraine on Ministerial Road, 0.65 mile south of Tuckertown Four Corners, in central part of Kingston quadrangle.

View of Charlestown moraine from the north. The moraine rises abruptly with a steep north slope. This slope is the north side of a ridge-like feature (look back at it as we travel into the moraine) that parallels the trend of the moraine. Though not shown as such on the geologic map (Kaye, 1960), it probably should be classified as a colluvial rampart, that is, a talus that accumulated against the north side of the ice core that underlay the Charlestown moraine after ice to the north had disappeared (to be discussed in more detail under Stop 3). The moraine is 1.4 miles wide (north-south) here, which is close to its maximum width. We are about 1.5 miles from its eastern end.

EN ROUTE TO STOP 4.

As we cross the moraine, notice the ridges and hills on both sides of the road. Seen from the air many of the ridges are sinuous to angular in plan, and the hills, or mounds, are oval to subround. A striking feature of the mounds is that they have flat tops commonly surrounded by a low rim. Just right of the road is Broad Hill, one of the best formed of the rimmed mounds. These are called ice-block casts (Kaye, 1960) and are thought to represent sediment that accumulated in depressions in the ice core that underlay the moraine during its formative years. These holes were caused by the more rapid melting of some blocks of ice, in comparison to the rate of melting of the surrounding ice.

The road descends to the sloping plain south of the moraine. We then go east along the south edge of the south edge of the moraine and the north edge of the outwash plain that heads up to it (US 1); then south on Matunuck Beach Road.

STOP 4. Hilltop south of Matunuck School (Blackberry Hill).

This gives us a general view of the Charlestown moraine and the terrain to the south and east of it.

South of the moraine, a surface of low relief grades gently south to sea level. This sloping plain consists of broad coalescing fans of outwash that originated at the ice front of the Charlestown moraine. Projecting through the outwash in several places, including the site of Stop 4, are low elliptical till-mantled hills (drumlins?) and a few patches of ground moraine that were not buried by outwash.

The till south of the Charlestown moraine seems to have about the same composition and degree of oxidation an soil development as the till in the moraine and north of the moraine. For these reasons, it may be about the same age as the moraine.

The Charlestown moraine is largely made up of ridges and mounds. The ridges, generally sharply sinuous to curved in plan, range from 5 to 100 feet in height and from the pattern they inscribe on the map (Kaye, 1960) appear to be crevasse or ice-fracture fillings.* The mounds have about the same range in height as the ridges and commonly have a flat top rimmed with a low ridge which also reflects a crevasse, or ice-fracture filling origin. It is suggested that these mounds represent sedimentation in holes in the ice. The holes resulted from the more rapid melting of blocks of ice isolated by fractures and the rimmed tops reflect these marginal fractures by a topographic inversion (Kaye, 1960). Here again, the reasons for preferential melting could profitably be discussed.

The Charlestown moraine is thought to have formed because of a belt of shear planes along the ice front. This resulted in a band of dirty ice in the marginal zone, which in turn produced a belt of thick ablation moraine. As the underlying ice melted, the ablation moraine shifted both by sliding and water transport into low places on the ice surface. The present topography of the moraine is essentially an inversion of the ice surface during the last stages of wastage--that is, high places on the ice core are represented by topographic lows, and ridges and mounds mark places where core ice was thin or absent.

The cleaner ice north of the moraine melted more rapidly than the debris-covered ice. As a result, for a long while the Charlestown moraine had a thick ice core that was isolated from the ice sheet to the north. Drainage from the deglaciated tract north of the moraine was partly submoraine, that is, meltwater flowed beneath the surface of the moraine through ice tunnels and enlarged crevasses in the ice core. In the Kingston moraine this submoraine drainage seems to have been largely localized at two places. These are both marked by deep pond-filled kettles and a sag in the crestline of the moraine. In short, there is a deficiency of material making up the moraine along these drainageways. This is probably the result of the flushing action of the subsurface drainage, washing away rock debris in the crevasses and englacial debris from the walls of the drainage channels.

These sags can be seen from Stop 4. One is north of Stop 4 and the other is to the WNW. It is interesting to note that the outwash fans head up to these drainageway sags and that a series of ponds and channelways also head up to what must have been the springs at the outlets of the submoraine drainage.

About a mile northeast of Stop 4, the ridges and mounds of the Charlestown moraine decrease rather abruptly in height and the moraine blends into a low hummocky topography that is marked here and there by low ridges, angular to sinuous in plane like the ice-fracture fillings of the Charlestown moraine but on a reduced scale.

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*("Ice-fracture filling" is preferable to "crevasse-filling" as a term here because to some, "crevasse" denotes a dynamically formed fracture. The fractures indicated, on the other hand, do not have the pattern or the orientation of the typical crevasse fractures resulting from ice movement. They seem to suggest tension (?) fractures that might, for example, form in massive stagnant ice because of stresses brought on by unequal melting. This problem would be worth discussing here.)

This low hummocky area makes up the southeastern part of the Kingston quadrangle and extends from the shore north to Wakefield. Two large salt ponds, Point Judith Pond and Potter Pond, are situated in this belt.

The low hummocky area is underlain mainly by gravel and sand but interbedded with these are rather extensive lenses of till. The till is dark gray in color, unlike the nearly white till of the Charlestown moraine, and is rich in the graphitic metasedimentary rocks of Pennsylvanian age of the Narragansett basin. There is a zone of mixing along the east end of the Charlestown moraine and the western edge of the low hummocky area where debris both from dark Narragansett basin rocks and light crystalline rocks occur together in the drift.

This low hummocky terrain is thought to represent a thick and relatively extensive ablation moraine. This is in contrast to the Charlestown moraine where the ablation moraine was confined to a narrow marginal zone of dirty ice. It is referred to on the Kingston quadrangle map as the "Ablation-moraine complex of the Narragansett basin ice". It grades both upward and northward into deposits that can be called ice-contact deposits. The boundary between the two types of deposits is arbitrary.

The ablation moraine complex of the Narragansett basin ice is probably the same age as the Charlestown moraine and may represent a lobate projection of the ice sheet in this section beyond the line of the Charlestown moraine. The narrow belt of moraine-laden shear planes of the Charlestown moraine gave way to a broader development of shearing and dirty ice in the Narragansett basin lobe. On melting, the difference in englacial moraine per unit area of ice (greater in the Charlestown moraine) produced a difference in the ultimate thickness of ablation moraine, and thus in the resulting morainic topography.

EN ROUTE TO STOP 5.

We will return to Rte. 1 and travel east along the toe of the moraine. Then the buses will travel northeast along the edge of the ablation moraine complex of the Narragansett basin ice to Wakefield, and then south along Point Judith Road. This road follows the crest of a ridge that is shown on the surficial map of the Narragansett Pier quadrangle as the Point Judith moraine, believed to have been deposited at the west side of the Narragansett Bay-Buzzards Bay ice lobe. The topography of moraine ranges from smoothly rolling to moderately knobby, and is more irregular to the south; but nowhere does it show the very sharp topography and distinctive form elements of the Charlestown moraine. The material is dominantly till, generally contains thin layers and lenses of sand, gravel, and silt, and was evidently deposited as ablation moraine. Known depths to bedrock range from 10 feet near the west end of Clarke Road to 95 feet at Fort Greene.

Continue south on Rte. 108, then west almost to Sand Hill Cove.

STOP 5. Shore cliff 0.5 mile northwest of Point Judith lighthouse, in southwest corner of Narragansett Pier quadrangle.

If the weather is clear, we will see Block Island 13 miles south, about at the position of maximum extent of the last ice sheet.

This cliff exposes ablation-moraine deposits, consisting of till and till-like material interbedded with sand and silt. The bedding is more-or-less deformed, presumably as a result of collapse, but some of the strong contortion in the upper part may be frost involutions. On top is late-glacial eolian sandy silt with ventifacts (wind-abraded stones). The beach gravel is coarse, poorly rounded, and thin, and lies on a platform eroded in till.

Most of the stones are of nearby crystalline rocks, especially the reddish granite and pegmatite as at Stop 9. The abundant gray Pennsylvanian sedimentary rocks were carried southwest from the Narragansett basin. Rare red sandstone and rhyolite come from the northwest part of the basin, near Attleboro. Two cobbles of cumberlandite (magnetite-rich peridotite) found on the beach here represent the west edge of the indicator fan of this very distinctive rock, derived from a small outcrop area 44 miles north (just east of Woonsocket).

The short, low cliff just west of the main cliff shows a soil profile developed under poorly drained conditions. The sag between these cliffs is the landward side of a former shallow kettlehole, now breached by marine erosion. A remnant of an organic deposit formed in this kettle occurs on the beach, covered by beach gravel; it contains abundant wood (much of which shows beaver tooth marks) and a few spruce cones. Pine wood from this deposit gave a radiocarbon age of 10,906 ± 112 years (OWU-22).

EN ROUTE TO STOP 6.

Travel north on Ocean Road. At Fort Greene, a boring west of road pentrated about 95 feet of glacial deposits on top of granite; east of road, near old coastal observation building, is a 34 foot granite boulder, the largest glacial boulder in this area. Continue north past the broad sand beach at Scarborough.

STOP 6. Shore point at end of Newton Avenue, midway between Indian and Gunning Rocks, in south part of Narragansett Pier quadrangle.

The shore here is composed of reddish granite, with many crosscutting dikes of coarse pegmatite and some inclusions of older schist (probably the Pennsylvanian rocks). Close to the end of the avenue, the granite shows glacial grooves from N 20° E. Glacial erosion controlled by joints in the granite produced stoss-and-lee topography: gentle upstream or stoss slopes and steeper lee slopes. On the southwest side of the point, till buries the main lee scarp. Wave erosion has stripped off till, but has eroded relatively little granite except in zones of close jointing. Southward from the point, joint blocks are progressively worn into rounded boulders by wave action in storms. Some patches of granite show distinctive salt weathering. This bedrock shore is of course more stable than is a shore composed of easily eroded glacial deposits as at Stop 5.

EN ROUTE TO STOP 7.

Travel north through Narragansett Pier, then west to US 1. Go north on US 1.

STOP 7. Esker, Pendar Road (formerly Old Post Road), 0.4 mile north of Shermantown Road, in southwest part of Wickford quadrangle.

Just before the stop, the south part of Pendar Road crosses a somewhat collapsed gravel plain, deposited by glacial melt-water streams that drained southwest from the ice onto the upland. The esker is the cast of one of the streams, and is part of the strongly collapsed ice-contact head of the deposit, which contains many kettles. The topography is very well shown along a trail that leads northwest from the road, at the southwest end of the esker. The road follows the crest of the esker for a short distance. Here as at many other stops we can see some of the diversification of habitats caused by glaciation.

The esker is part of the kettle ice-contact head of sequence 2a, which drained southwest over the upland to Saugatucket River. This head stands nearly 100 feet above the deposits of sequence 4, which drained southeast along Mattatuxet River.

EN ROUTE TO STOP 8.

We travel north and northwest, and then west on West Allentown Road, across deposits of sequence 4 and 3 and "morainic kames". The morainic kames, which are unpredictable mixtures of till and water-laid materials, are the first ice-hole deposits laid down as the ice melted away from the moraine to the west. We travel across the moraine, and then onto the outwash plain west of it.

STOP 8. Indian Corner Road, east of Slocum.

This stop is in the midst of the potato fields that occupy most of this extensive outwash plain. The plain is correlated with the moraine that lies along the boundary between the Slocum and Wickford quadrangles. A high part of the moraine (about 80 feet above the outwash plain) lies directly east of this stop.

EN ROUTE TO STOP 9.

Return to US 1, travel north Rte. 102, then east.

STOP 9. Pit on north side of Route 102, 0.3 mile east of circle intersection with Routes 2 and 4, in west-central part of Wickford quadrangle.

This pit in a kame shows ideal ice-contact features. The materials range from sand to boulder gravel, mostly well bedded and well sorted, but some poorly sorted. There is much lensing and abrupt change in texture. The materials were deposited on and against motionless remnants of glacier ice, and the melting of that dead ice produced collapse, with strong faulting and folding of the beds.

EN ROUTE TO STOP 10.

North on Route 2, and west at Pontiac on north side of Pawtuxet River floodplain. Floodplains are a very minor part of the Rhode Island landscape, and are very subject, as here, to spoilation by man: pollution (note sewage disposal plant) and filling (for highways and buildings)! Continue west, past Natick, up the west scarp of Narragansett basin (basal Pennsylvanian conglomerate on southwest side of road) and across upland to Harris; then north on Lippitt Avenue and east on private road.

STOP 10. "Rottenstone" pit north of Harris, on west side of private road, 800 feet north of 258 foot intersection, northeast part of Crompton quadrangle.

This weathered granite is in one of several extensive areas of weathered bedrock in Rhode Island, mostly in coarse granitic rocks, and more then 15 feet thick in some places. The weathering generally consists of disintegration caused by slight chemical decompostion of feldspar and biotite, and commonly reveals a platy structure. Spheriodal weathering controlled by joints produces core stones, which here are flattish ellipsoids. This weathered rock presumably is only the lowest part of a once much thicker weathered zone (comparable to that of the Piedmont province along the east side of the Appalachians, south of the limit of glaciation), but the rest has been eroded away, mostly by the successive glaciers. It is overlain here by unweathered light-gray granitic till; therefore, the weathering is older than the last glaciation and perhaps than the entire Ice Age.

EN ROUTE TO STOP 11.

(8 miles) South through Harris and West Warwick to Crompton, mostly on till-bedrock hills; then southwest on New London Turnpike and west on Division Road, mostly on a broad terrace of glacial sand and gravel.

STOP 11. Sand pit on north side of Division Road at 277 foot intersection, southeast of Mishnock Pond, in southwest part of Crompton quadrangle.

This is the eastern of two large pits in thick sand that was probably deposited in a glacial lake. On the east side of the entrance to the pit is exposed the postglacial soil, developed on late-glacial windblown sandy silt that overlies the glacial-lake deposits; this soil is now buried by sand blown from the pit since the pit was opened. The pit has been worked hardly at all for 15 years or more. During this time, small phytogenic dunes of sand held by clumps of vegetation have been built at the east side of the pit; the plants principally responsible are sweetfern (Comptonia peregrina), bramble (Rubus), and a sedge (Carex). Also during this time, the west and northwest sides of pebbles in some parts of the pit have been polished by wind-driven sand. The sand also shows wind ripples and other features. This "Desert of Rhode Island", like other such "deserts" in New England, was caused by destruction of the original vegetation by man.

END OF TRIP

THE GEOLOGY OF CAMBRIAN ROCKS OF CONANICUT ISLAND, JAMESTOWN, RHODE ISLAND

by

James W. Skehan, S. J.
Weston Observatory
Dept. of Geology
and Geophysics
Boston College
Weston, MA 02193

Nicholas Rast
Dept. of Geology
University of Kentucky
Lexington, KY 40506

Daniel F. Logue
Southeastern Division
EXXON Company
P.O. Box 61812
New Orleans, LA 70161

INTRODUCTION

The geology of Conanicut Island was mapped by Dale (1885a, 1885b). He correctly differentiated the phyllites of southern Conanicut Island from the flora-rich schists of the Pennsylvanian Rhode Island Formation that make up its northern half (Fig. 1). He did not, however, have a basis for age designation but determined that they were lithologically unlike the fluvial metasedimentary rocks of Pennsylvanian age. Subsequent mapping by Nichols (1956) included the phyllites as part of the Rhode Island Formation and these results were incorporated in the geologic map of Rhode Island (Quinn, 1971).

Skehan and others (1976, p. 459) noted that "the structural features at Beavertail suggest that the rocks may have a history of repeated deformation that is more complex than other parts of the Narragansett Basin and may therefore antedate the fossiliferous schist (of Pennsylvanian age) of Northern Conanicut Island near Jamestown." Subsequently trilobites yielded a Middle Cambrian age (A. T. Smith, 1977; Skehan and others, 1978). Field mapping, sedimentational, and structural studies continue.

STRATIGRAPHY

A preliminary description of the stratigraphy was given by Skehan and others (1976), and in greater detail by Skehan and others (1978), and by Murray and Skehan (1979). These descriptions, drawn first from the southeastern shore of Beavertail (Stop 1), form the main elements of the stratigraphic succession which is most readily demonstrable on the basis of sedimentary facing criteria and the presence of trilobite fauna. The trilobites diagnostic of age have been derived from Units A and B (Table 1) now called the Lion Head member of the Jamestown formation and the Short Point member of the Fort Burnside formation respectively.

Ongoing studies show that structural complexity due to polyphase folding of these phyllites is further increased by displacements due to tectonic sliding, a large scale dislocation, which predates but may be approximately synchronous with the first folding episode affecting these Cambrian rocks. We present in Table 1 a revised stratigraphic correlation.

The following are descriptions of the stratigraphic units:

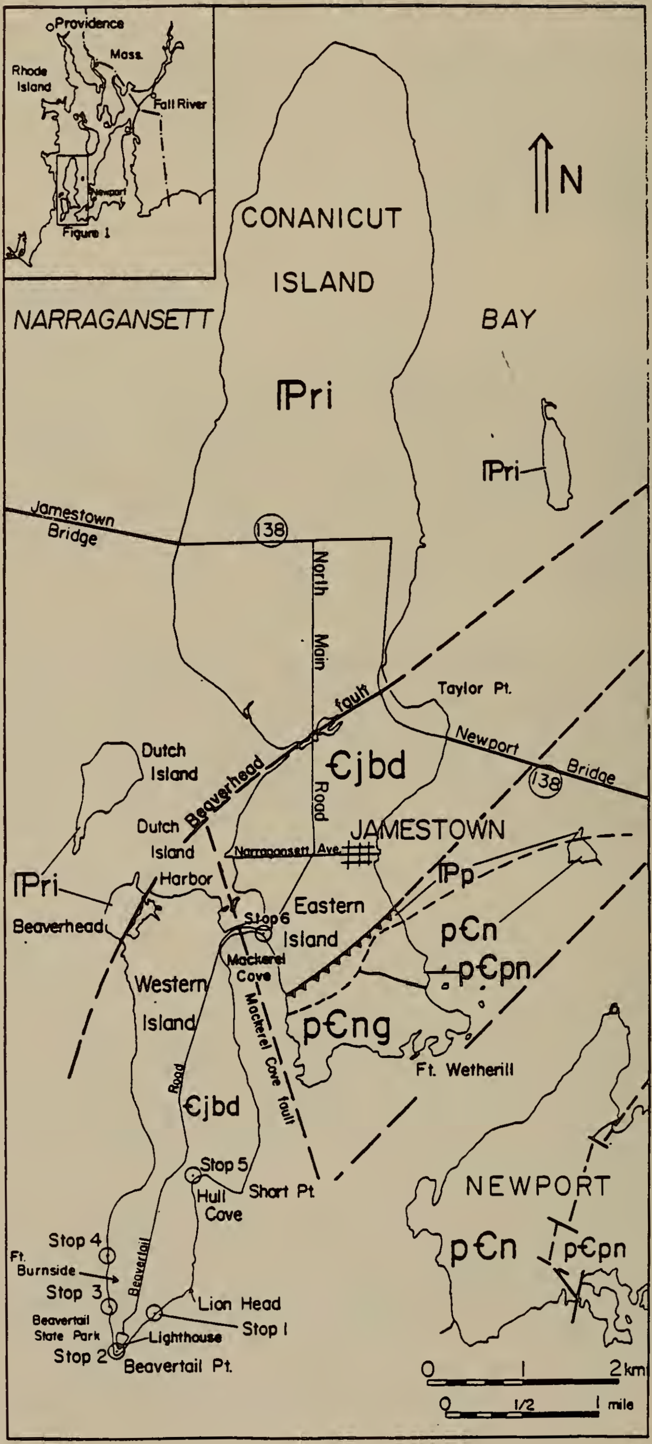

Figure 1. Generalized geological and location map showing the distribution of Cambrian rocks of Conanicut Island, Narragansett Bay with respect to Precambrian and Pennsylvanian; showing the location of Stops and type localities of Cambrian units, Єjbd. pЄn - Newport formation; pЄpn - Price's Neck formation; pЄng - Newport granite; Pp - Pondville Formation; Pri - Rhode Island Formation.

Jamestown formation

The Jamestown formation forms the basal part of the Cambrian succession. Nowhere, however, are all three of the members in stratigraphic contact with each other and therefore the stratigraphic position of the Lion Head member, which contains the age diagnostic trilobites, is inferred but not known with certainty. However, on the basis of data from Stop 6 the Hull Cove member is placed below the Lion Head. The Hull Cove may be the facies equivalent of the Beavertail Point member. The Jamestown formation consists of fossiliferous green and gray phyllite with minor amounts of black phyllite, and buff-and white-weathering siltstone. It is estimated to be about 200 m thick.

Beavertail Point member. This unit consists of 80 to 90 percent green phyllite comprised of the assemblage quartz-chlorite-muscovite-feldspar ± siderite ± paragonite. Buff-and white-siltstone makes up about 8 to 15 percent of the member; white siltstone beds (< 1 percent of the siltstone), rarely exceed 2 cm in thickness). The buff siltstone, 2 mm to 30 cm thick is micaceous (approximately 10 percent muscovite), internal laminae are generally 1 mm thick, and may contain up to 40 percent dolomite. When siltstone beds are present the bedding is recognized as cyclical. Black phyllite, comprising about 5 percent of the member, has the same mineral assemblages as the green phyllite; the black color may be due to graphite. Dolomite concretions, 6 to 40 cm, are present but are not as abundant as in the Dutch Island Harbor formation. Ichnofossils, present in this member, will be seen at Stop 2 and will be discussed further under Paleontology.

Skehan and others (1976)	Skehan and others (1978) and Murray and Skehan (1979)	This Paper
Unit a	Unit E	
Unit b	Unit D	Dutch Island Harbor formation
Unit c	Unit C	Fort Burnside formation Taylor Point member
Unit d	Unit B	Short Point member
Unit e	Unit A	Jamestown formation Lion Head member Hull Cove member Beavertail Point mem.

Table 1. Correlation of Cambrian Stratigraphic Units of Conanicut Island.

Hull Cove member. This member consists dominantly of green phyllite on the western island (Fig. 1) and of gray phyllite on the eastern island. White siltstone is the dominant coarse clastic on both islands but buff siltstone is rare. The white siltstone beds, rarely exceedingly 9 cm, consist of the assemblage quartz-chlorite-muscovite-carbonate; carbonate, however is substantially less than in the buff siltstone. On the eastern island the phyllite is gray and the bedding cyclical with cycles being up to 45 cm in thickness and

PALEONTOLOGY AND AGE OF ROCKS

Three different trilobite forms have been recovered from the sequence just described (Skehan and others, 1978). The most useful for age dating is Badulesia tenera (Harrt) (Fig. 2a through 2c), a widespread species of medial Middle Cambrian age. This species is known from New Brunswick, Eastern Newfoundland, southern Germany, northern Spain and eastern Turkey. Closely related species are also known from southern France. Close stratigraphic control is provided by Sdzuy (1967) for northern Spain, where he shows that this species characterizes a subzone within the Middle Cambrian Badulesia zone and that it correlates approximately with the lower part of the Paradoxides paradoxissimus zone of northern Europe. The next most abundant trilobite is an indeterminate species of Paradoxides (s.l.). The most complete specimen (Fig. 2d) consists of half of a thorax and the anterior part of a cranidium that has been separated and rotated 90% from the thorax. These fragments suggest that the individual was at least 45 cm long.

A third species not figured is represented by an unidentifiable fragment with a strong granular orientation (Skehan and others, 1978).

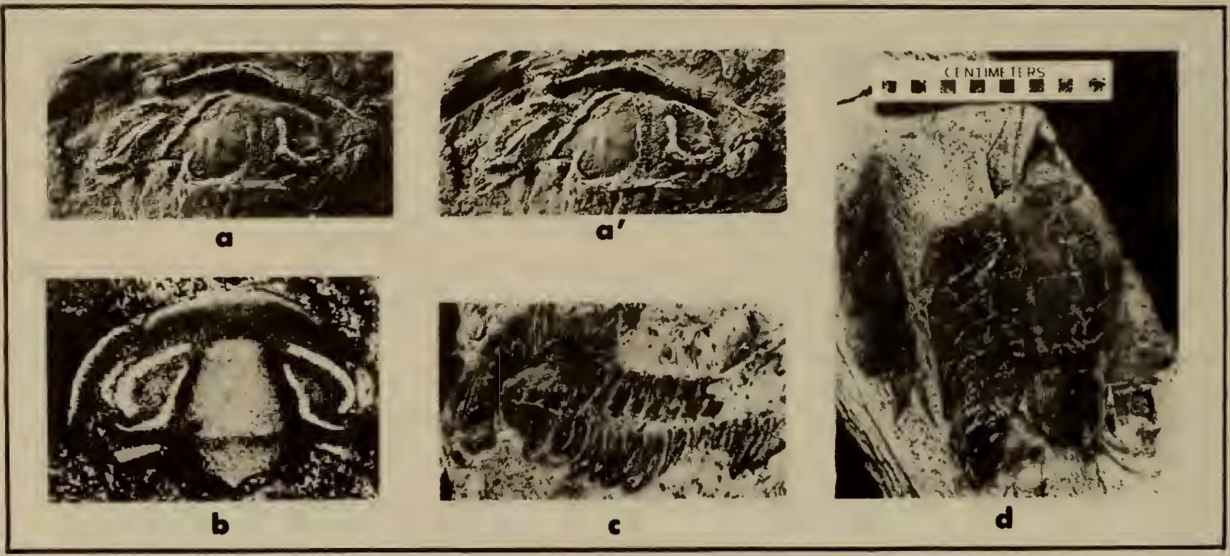

Figure 2. Middle Cambrian trilobites, (a,a') Stereopair of cranidium of Badulesia tenera (Hartt), Conanicut Island, Rhode Island, x 1 (horizontal dimension of photo, 48 mm); (b) cranidium of Badulesia tenera (Hartt) (Sdzuy, 1967, Pl. 6, Fig. 3) from Eastern Asturias, Spain, x 0.6 (horizontal dimension, 75 mm); (c) left side view of laterally compressed, partially complete specimen of Badulesia Tenera (Hartt), x 1 (horizontal dimension, 48 mm); (d) thorax and anterior cranidial margin (to left) of Paradoxides sp., x 0.2 (horizontal dimension, 240 mm) (Skehan and others, 1978).

progressing upward from white siltstone to black phyllite to gray phyllite. Other than in respect to carbonate there is no major difference in lithology. Trilobite fragments, as well as minor ichnofossils, have been observed at Hull Cove.

Lion Head member. This gray phyllite consists of the same mineral assemblages as the corresponding parts of the other two members of the Jamestown formation but differs from them in the absence of coarser clastics and in the presence of fluorapatite nodules and abundant trilobites and trilobite fragments. The unit is massive without conspicuous bedding; the bedding, however, is seen as a minor color variation in the phyllite and is on the order of 3 to 8 cm.

Fort Burnside formation

The Fort Burnside formation here is named for the U.S. Harbor Command Control Post formerly occupying part of the property now being developed as the Bay Islands Park system. It consists of two members and is a distinctive, cyclically bedded unit of buff- and white-weathering coarse siltstone overlain by black and gray phyllites. This formation is approximately 50 m thick.

Short Point member. The cyclical sedimentational units of this member consist of buff siltstone and black and gray phyllite. The development of the cycles is such as to produce an interlayering of siltstone laminae and black phyllite which gradually gives way to black phyllite without siltstone. The siltstone beds are micaceous, calcareous, and have abundant ripples, cross lamination, and truncation surfaces. Both phyllites appear to be structureless except that fluidization structures are common in the lower 20 m of the unit. This member has a conspicuous development of soft sediment fault offsets.

Taylor Point member. This member is thin, approximately 10 m, and differs from the Short Point member by the absence of gray phyllite from the sedimentary cycles. South of Lion Head chasm (Fig. 1) the siltstone tends to be buff in color and micaceous as well as calcareous. Elsewhere, as north of Lion Head and at Taylor Point the phyllites are white and cleaner, containing less than 5 percent carbonate and less than 10 percent mica. This unit tends to be broken up either by soft sediment deformation, as is more likely, and/or by tectonic dislocations. Going up section in the Taylor Point member there is a gradual increase in the amount of unoxidized shaley material and a decrease in the amount of sand, a feature which reaches maximum development in the overlying Dutch Harbor Island formation into which the Fort Burnside formation grades.

Dutch Island Harbor formation

The Dutch Island Harbor formation is a black rhythmically bedded phyllite consisting of beds 1 to 4 cm in thickness, commonly containing 1 cm-deep scour channels. There is an abundance of carbonate concretions which have a shaley inner core and cone-in-cone structures in the outer core. The Dutch Island Harbor formation is about 100 m thick.

These fossils have been derived from the Lion Head and from the basal part of the Short Point member. Most of the more than a dozen fossils collected for use in the study by Palmer (Skehan and others, 1978) came from Lion Head, north of Lion Head chasm, and from just south of it as well. The Lion Head member, wherever it is found, is typically rich in fossil hash, as are also parts of the Beavertail Point and Hull Cove members. Logue found an approximately 6 cm long complete individual trilobite identified by Palmer (pers. comm. to Skehan, 1980), as an infantile form of Paradoxides. That trilobite was found at the top of the Hull Cove member adjacent to the contact with the Lion Head north of Short Point of Stop 5 (Figs. 1 and 5).

Ichnofossils or worm burrows from the Beavertail Point member of Stop 2 (Fig. 6) have been identified by Ronald K. Pickerell (written comm. to D. F. Logue, 1981). Three ichnogenera were identified as Palaeophycus (= Buthrotrephis), Planolites, and Helminthopsis. Logue has also found ichnofossils in the Hull Cove member (Stop 5).

In summary, diagnostic trilobites have been found in the Lion Head and Short Point members; trilobite hash, in abundance not only in the Lion Head but also in the Beavertail Point members. An isolated trilobite and fragments have been found in the Hull Cove member of the Jamestown formation, and additionally ichnofossils have been found in the Beavertail Point and Hull Cove members of the Jamestown formation. Thus the members of Jamestown formation have yielded variably abundant fossil material as also has the base of the Short Point member of the Fort Burnside formation. To date, however, no fossils have been reported from the Taylor Point member or the Dutch Island Harbor formation at the top of this succession of Middle Cambrian rocks.

The sedimentological characteristics of these rocks, discussed below, suggest that these formations are a unified package of sediments having an uninterrupted history of deposition. Thus the age, even of the upper part, in which as yet no fossils have been found, is probably limited to Middle Cambrian.

ENVIRONMENT OF DEPOSITION

The same mineral assemblages are present in the gray, green, and black phyllites of the Lion Head and Hull Cove members of the Jamestown formation, of the Fort Burnside formation, and of the Dutch Island Harbor formation. The lower two formations represent a coarsening upward sequence but the rhythmically layered Dutch Island Harbor formation represents a trend towards a quieter environment of sedimentation (Skehan and others, 1978).

Geologic mapping by one of us (D.F.L.) of the entire Cambrian outcrop area (Fig. 1), a representative portion of which is shown as Figures 4, 7, and 9, has led to the conclusion that at least the Beavertail Point and Hull Cove members may be lateral equivalents of each other. Additionally the Lion Head member overlies the Hull Cove member (Stops 5 and 6).

Pickerell (written comm. to Logue, 1981) having examined the ichnofossils advanced the opinion that since deep-water Cambrian rocks are poor in trace fossil density and diversity, a more shallow water regime would be favorable to their development. Other characteristics of the sediments are consistent with a relatively shallow water, relatively near shore shelf environment. These include the green coloration, due to chlorite, of the Beavertail Point and part of the Hull Cove members. Additionally, these rocks are rich in other minerals possibly in large part derived from a volcanic source terrain. The gray to black phyllites may have been deposited on the outer contenental shelf, possibly in a depression which was subject to high organic and phosphate productivity due to upwelling, giving the dark coloration and forming nodules, beds, and lenses of phosphate.

STRUCTURE

General. This Cambrian terrain is replete with a wide variety of structures of various relative ages. An objective of the field stops and traverses will be to demonstrate the relative and, as possible, the absolute timing of structural events. Some structures were developed as pre- and syn-lithification features, others probably developed as synorgenic structures, and still others were developed as late brittle rock features.

Tectonic slides and F_1 folds. Tectonic slides have been defined by Bailey (1910) as fold-faults or, in modern language, synkinematic fracture discontinuities, commonly lacking signs of cataclastic disturbance. They have recently been reviewed by Hatton (1979) and form an important element of tectonic deformation in metamorphic rocks of all grades of metamorphism. The term tectonic slide is preferred to thrust because often the original movement on these discontinuities is indeterminate and they may have had a distensional, rather than compressional origin.

Features, such as opposing sedimentary topping directions and/or breccias near contacts, pre-cleavage ramp faults, and others associated with tectonic slides are extraordinarily well displayed in these rocks and provided the basis for recognizing these structures. Tectonic slides here antedate structures associated with F_1 folds but probably the two are nearly contemporaneous and possibly are an integral part of the same tectonic activity.

Thus the age of tectonic sliding and F_1 folding may be as early as late Middle or Late Cambrian time. The tectonic sliding may have been in response to uplift and consequent instability of the outer shelf or upper continental slope causing large blocks of the entire Middle Cambrian succession to be transported on top of other parts of the same succession but deposited in a recognizably different sedimentary environment within the same basin. Some folding identified as F_1 may be essentially contemporaneous with sliding and other F_1 folds may represent a continuing deformation of the autochthonous, together with the allochthonous successions.

The most readily recognized F_1 folds are those with upright northerly-striking axial planes. A fabric interpreted as S_1 cleavage is axial planar to early folds and may be examined at Stop 1 (Fig. 5), and this and other F_1 folds will be examined at Stops 1, 2 and 3.

Structures Associated with F_2 folds. F_2 folds in Cambrian rocks of Conanicut Island and associated axial plane cleavage are probably the most conspicuous of structural features. Typically F_2 fold axes trend approximately N-S.

On eastern Conanicut axial plane cleavage ranges from horizontal to gently dipping to the west; on western Conanicut it dips on average more steeply to the west. Lenticular carbonate porphyroblasts elongate in the plane of S_2 may record the movement direction of thrust sheets or nappes which may have been responsible for the F_2 folds and gently dipping cleavage.

Post F_2 Structures. Such features include thrust faults associated with the Alleghanian orogeny; late normal faults, kink band folds, and a transcurrent fault. Although Alleghanian thrust faults may be widespread, at present they have been proven in this Cambrian terrain only on the eastern shore of Mackerel Cove where the Jamestown thrust, a name newly proposed here, thrusts Pennsylvanian Pondville formation, lying non-conformably on the Precambrian Newport granite (Fig. 1),. as a unit on Cambrian phyllites (Stop 6). The Newport granite and older, Late Precambrian rocks of the Price's Neck formation near Fort Wetherill (Fig. 1), are cut by easterly-dipping faults which we tentatively interpret as Alleghanian as well.

Late normal faults are widespread in this terrain. Kink bands are well developed in many places and are typically associated with late extensional faults.

A possible transcurrent fault is the Beaverhead fault which separates the Cambrian phyllites in the lower greenschist facies of metamorphism of southern Conanicut Island from the higher grade Pennsylvanian schists of northern Conanicut Island. The former fault and the rocks which it separates have been described by Murray and others (1979), Murray and Skehan (1979), and Burks and Mosher (1980 and this volume). The Mackerel Cove fault, newly proposed here, offsets the Jamestown thrust as well as the rocks transported by it. It is not yet known whether the Beavertail fault is offset by the Mackerel Cove fault which is probably dextral, or whether the Mackerel Cove is a branch of the Beavertail system and essentially contemporaneous with it.

METAMORPHISM

The phyllites of the eastern island have been mapped in the chlorite zone of metamorphism and those of the western island in the biotite zone (Nichols, 1956; Quinn, 1971). We now recognize that the Cambrian phyllites of neither island record metamorphism higher than chlorite zone. The only megascopically identifiable minerals in these phyllites are pyrite and siderite, the latter showing an overgrowth of siderite on a similar ferroan carbonate. The Beavertail fault may displace metamorphic isograds in Pennsylvanian schists of northern Conanicut Island. Quinn (1971, Plate 1) shows the northwesterly-trending metamorphic isograds of northwestern Narragansett Bay as curving to the south and southwest. Accepting this trend in the north, and although the isograd locations on northern Conanicut have been in part remapped, the trend remains as Quinn portrays it as far south as the trace of the Beavertail fault (Gill, pers. comm., 1981). Thus one may conclude on the basis of the curvature of isograds, that the Beavertail fault is dextral, a conclusion supported by evidence from offsets of magnetic lineations (Miller and Frohlich, 1981).

ROAD LOG GUIDE

The locations of field stops for this excursion are shown on Figure 1; certain features will be illustrated in greater detail in subsequent figures. The directions in this guide are designed for smaller self-led groups, and therefore, differ slightly from the route which we will actually follow due to easier access to certain stops as a result of special permission of landowners.

Mileage	
0.0	Start trip at the junction of Route 138 with North Main Road marked by a traffic light in a valley at a four way intersection. Those coming from the west will arrive by taking Route 138 east across the Jamestown Bridge (no toll) proceeding east for an additional 0.7 miles. Those coming from the east will arrive by taking Route 138 west across the Newport Bridge (toll $2.00) and continuing west for 1.6 miles. Bypass the center of Jamestown (unless you are familiar with the route to Beavertail). Proceed south on North Main Road.
0.7	Jamestown Historical Society windmill (1787) on left (east) side of North Main Road.
1.3	Trace of the Beaverhead fault (covered), separating the Cambrian from Pennsylvanian rocks, passes across the island under this tidewater lowland. Beaverhead Point may be seen to the right (southwest) in the middle distance.
2.0	Cross Narragansett Avenue in Jamestown and proceed south, at which intersection the name becomes Southwest Avenue.
2.6	Bear right and continue across the sand bar which ties the eastern island to the western island. Mackerel Cove on left (south), Dutch Island, and Dutch Island Harbor (type locality) are seen to right (north). Here the name of the road we are travelling becomes Beavertail Road, the only road leading to the parking area from which you will walk to the start of the traverse of Stop 1 (Fig. 3.),
5.3	Turn left (east) off Beavertail Road into Beavertail State Park; 100 m ahead on right may be seen a remnant of Fort Burnside, once a submarine communications center but now a part of the Bay Islands Park System.
5.4	Parking for Stop 1, overlooking the rockbound shore of the southeastern coast of Beavertail. Walk immediately northeasterly along the shore a distance of about 500 m (or about 1500+ ft) to Lion Head Chasm (Fig. 4). To reach Lion Head stay left near the upper shoreline exposures and walk carefully around the head of the Chasm, along the only path there, to the beginning of the traverse immediately N of the Chasm.

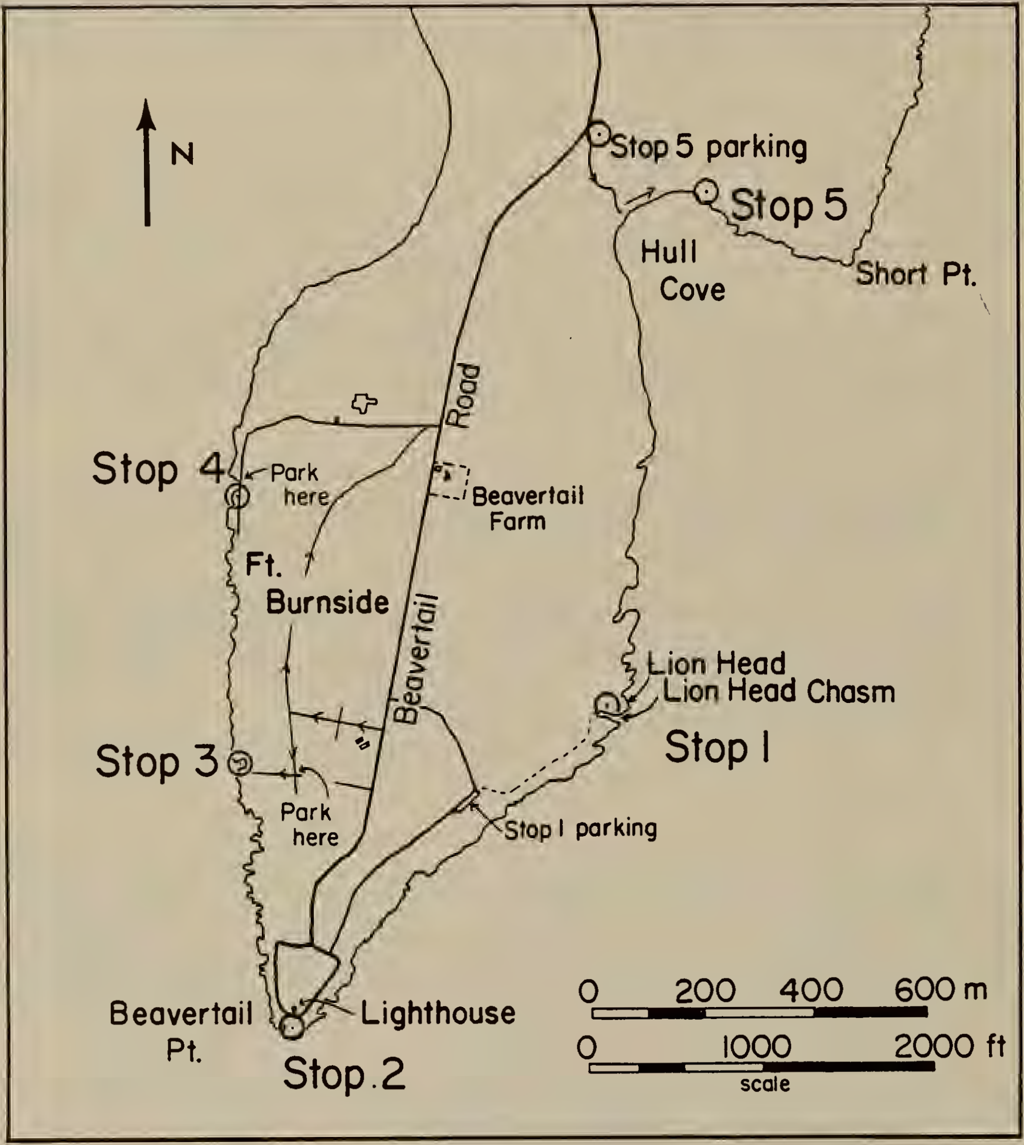

Figure 3. Location map for Stops 1-5, Beavertail and Hull Cove, Jamestown.

Stop 1. Cambrian succession, structures, and trilobite locality. Traverse from Lion Head SW to parking area. NO HAMMERS PLEASE; State of Rhode Island requires a permit to remove any rock specimens from the outcrop in this park.

Features to be observed here include:

A. The inverted stratigraphic succession. Along this traverse the entire Cambrian sequence with the exception of one member may be seen. From NE to SW one may examine the inverted sequence which from the base upward consists of: the Lion Head member of the Jamestown formation, the Short Point and Taylor Point members of the Fort Burnside formation, and the Dutch Island Harbor formation. At the southwestern end of the traverse the Beavertail Point member, in tectonic slide contact with the Dutch Island Harbor formation, will be examined. These informal stratigraphic names are introduced in this paper and their equivalence to unnamed, lettered stratigraphic divisions by Skehan and others (1976) and Skehan and others (1978) is given in Table 1.

B. The trilobite locality in the Lion Head member from which fossils diagnostic of a medial Middle Cambrian age were recovered (Fig. 2).

C. Structures associated with intraformational and interformational tectonic slides, as at 1-7 and 1-9; a variety of soft sediment deformation features possibly associated with slides and related instability of the sedimentational basin as between 1-4 and 1-5.

D. Folds and associated features. The dominant folds of this stop are F_2 folds and associated gently dipping S_2 cleavage. It is the latter that is chiefly responsible for this coastline being so different from that of the steep coastal cliffs of part of the west side of Beavertail (Stops 3 and 4). The F_1 folds of 1-6 and 1-8, with their associated S_1 cleavage, are apparently localized phenomena related to intraformational slides. F_1 folds on the other hand at Stop 3 (below) appear to be part of the larger F_1 structure deformed by the F_2 flattening event.

E. Late brittle faults and kink bands. A number of relatively late brittle deformation features may be seen, as at 1-4 and 1-10 along the well exposed trace of the Beavertail fault and its branches. Many of these contain slickensided vein quartz in the plane of the fault, as at 1-7, while others may be without quartz veins but truncate earlier veins.

Throughout many parts of this Cambrian outcrop area on Conanicut Island kink bands are well developed, as between 1-2 and 1-4 along the higher parts of the outcrop. These kink bands appear to be closely associated with the Beavertail fault and some of its branches.

Although the movement of these branch faults may not be great, it appears responsible for local offsets and rotation of blocks which produces changes in strike and dip of S_2 cleavage from block to block along this shore.

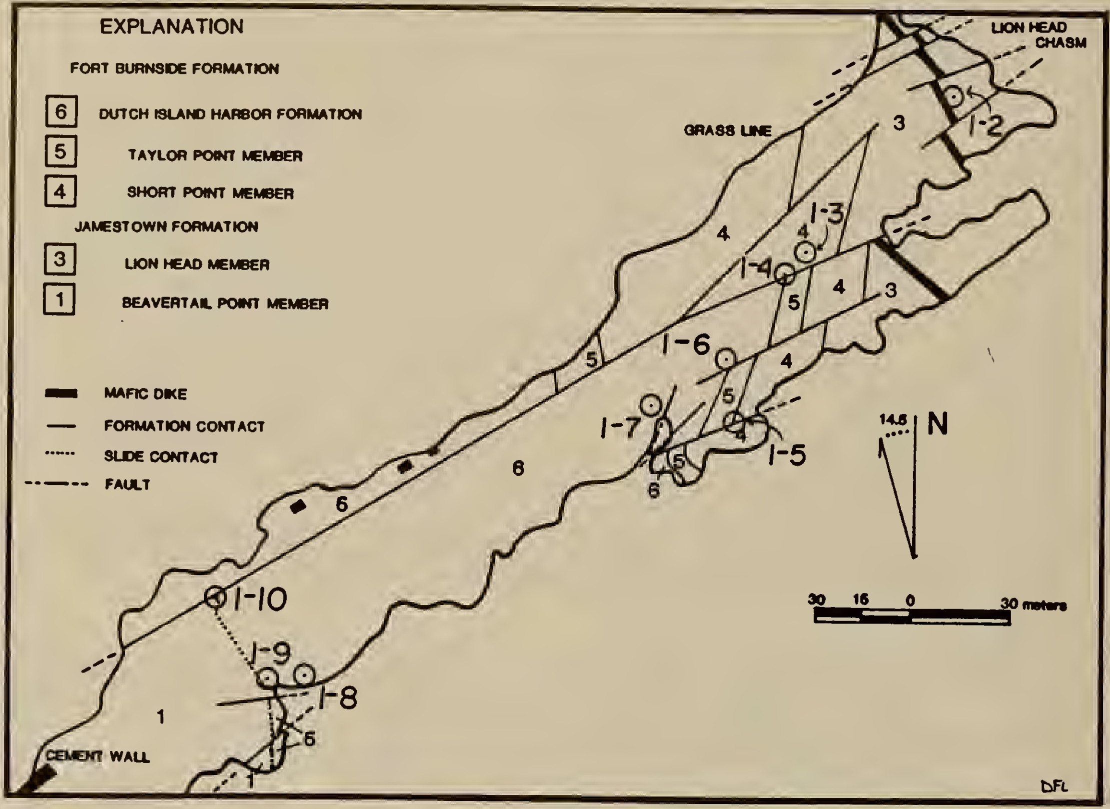

Figure 4. Geological sketch map showing location of stations on the Stop 1 traverse from Lion Head southwest to the parking lot (Fig. 3), eastern shore of Beavertail, Conanicut Island.

Specific features are noted at the following points along the traverse:

1-1. From this point Hull Cove and Short Point (type localities, Fig. 1) may be seen in the near distance to the north. In the middle distance are the cliff exposures of Newport granite of the eastern island near Fort Wetherill. Across Narragansett Bay to the northeast is Newport, the site of a field trip by Rast and Skehan (this volume). The lighthouse at the end of the Castle Hill tráverse (1-15 of Stop 3) may be seen on the rock cliffs on a bearing N. 65° E. from here.

This outcrop at Lion Head is about 40 X 40 m and forms the northern margin of Lion Head Chasm. Together with the cliff exposures just north of a second, smaller chasm, as well as the cliffs along the southern margin of Lion Head Chasm near 1-2, they are the source of the original fossils diagnostic of age recovered in 1976 (A.T. Smith, 1977; Skehan and others, 1978; Murray and Skehan, 1979).

This is the type locality of this member (description above in text). Note its characteristic massive, relatively uniform appearance except for the scattered, small, dark phosphatic lenses and chip-like masses (mudchips of Skehan and others, 1978). Note also the siderite porphyroblasts, elongate (N. 65°W. at 15°) in the S_2 plane.

A partial specimen of Paradoxides 18 cm long remains in the outcrop. Its nearly horizontal orientation, marking the bedding, forms an acute angle with the S_2 cleavage (N. 40°E.; 13°NW). Fourteen trilobites or substantial fragments have been collected from this locality and 1-2. Fragments of trilobites are abundant on the surface exposures of the Lion Head member wherever it is seen.

We urge that those who must collect something collect from the fossil hash which is abundant outside the State Park. The Paradoxides at this station cannot be collected intact because of the cleavage. Moreover it should not be collected because of its wide usefulness to classes of geology students and for public education field trips by the park naturalist. Therefore, we urge the continued preservation of this remnant of the Middle Cambrian for the enjoyment and education of present and future generations.

In passing along the head of the chasm rim to 1-2 note that the massive beds of the Lion Head are underlain by upturned beds of alternating gray and black phyllite with buff-siltstones of the Fort Burnside formation.

1-2. South side of Lion Head Chasm. A metamorphosed minette dike consists of the assemblage zoisite + quartz + biotite + plagioclase + calcite + accessories (Skehan and others, 1976). The dike (N. 25°W.; 25°SW) cuts the Lion Head member, has a chilled margin, is folded by F_2 folds and is cut by S_2 cleavage. The carbonate porphyroblasts near the dike are notably larger than the average elsewhere (elongation lineation - N. 30°W. at 0-15°). The fragments of this faulted dike form excellent markers for recording the apparent movement on the Beavertail fault and its branches.

A partial Paradoxides individual 10 m S. of this station has been left on the outcrop for the same purposes as noted above for 1-1.

1-3. Just north of the gully formed in the Beavertail fault zone. Characteristic lithology and bedding features of the Short Point member are well illustrated here in F_2 folds to which the dominant S_2 cleavage is axial planar. These have been figured in Murray and Skehan (1979, Fig. 12). Stratigraphic tops are to the NW as indicated by the upward-fining graded beds.

1-4. A gully between 3 m high cliffs of rock exposes the Beavertail fault (N. 60°E.; 60°NW), a post-F_2 structure (F_2 axis - N. 28°E. horizontal). Antithetic faults and branches of the Beavertail fault offset the stratigraphic units and the meta-minette dike of 1-2. The contact of the top of the Fort Burnside formation with the base of the Dutch Island Harbor formation is exposed in the cliff face southeast of the fault.

In passing from 1-4 to 1-5 the magnificently exposed section of the Short Point and Taylor Point members of the Fort Burnside formation may be observed. Here are displayed a wide range of sedimentational, soft sediment and tectonic structures. F_2 folds, whose axes (S. 10°W. at 15°), are well defined by thick buff-weathering siltstone beds, are easily observed.

1-5. This location near the high tide level can be recognized by the presence of the main development of a 0.3 m thick, buff-weathering quartz vein along a fault. Standing near the vein and looking north at a small cliff 5 m distant are seen F_1 folds, showing closure of beds again folded by F_2 movements and both limbs of F_1 cut by the dominant S_2 cleavage. These folds have been described and figured by Murray and Skehan (1979, Figs. 14A and 14B).

Follow the quartz vein SW to the contact with the base of the inverted Dutch Island Harbor formation. Here the truncation of the cross laminated ripples indicates that the Taylor Point member, faces into the Dutch Island Harbor beds.

1-6. Ten m WNW of the contact just described. Here may be seen F_1 folds with S_1 cleavage referred to above (Fig. 5).

1-7. Near a prominent steep cliff face covered with vein quartz 25 m due W of contact between Fort Burnside and Dutch Island Harbor formations noted above. A ramp fault may be seen in typical, rhythmically layered phyllites of the Dutch Island Harbor formation containing carbonate concretions, and phosphatic beds and lenses. The slide plane of this intraformational tectonic slide is marked by carbonate-bearing quartz veins deformed by F_2 folds which can be traced up the face of this cliff. The beds on either side of the slide plane become parallel to the north of the cliff face, whereas to the south they are at angles up to 25 degrees. This structure was figured by Skehan and others (1976, p. 465).

These earlier formed structures are cut by a quartz vein-filled normal fault (N. 60°E.; 55°SE.) the quartz preserving approximately down-dip slickensides. In passing to 1-8 one may walk along the lower "platforms" near the high tide mark to observe sedimentational features and the F_2 folds (N. 5°W.; axis horizontal) which are well exposed in cross section as well as on nearly horizontal S_2 cleavage surfaces.

Figure 5. Structural elements in the Dutch Island Harbor formation. S_2 is the flat surface on which the north pointing compass rests, (Murray and Skehan, 1979).

1-8. Here is the first of a series of nearly flat S_2 platforms just N. of a fault gully 15 m N. of the conspicuous contact between the dark phyllites of the Dutch Island Harbor formation and the pale green phyllites of the Beavertail Point member of the Jamestown formation. Here pre-F_2 folds, produced by slippage on quartz-filled intraformational faults, are seen between these faults. The same type of S_1 cleavage as was noted at 1-6 is developed here subparallel to the associated quartz-filled slide planes.

Carbonate concretions, associated with phosphatic and carbonate siltstone beds, record well developed F_2 folds.

1-9. At contact of the Dutch Island Harbor formation with the Beavertail Point member of the Jamestown formation. Here are well exposed F_1 and F_2 folds (Skehan and others, 1976), the former having axial planes which are upright and the latter parallel to the S_2 cleavage. We regard this contact as a tectonic slide which antedated the F_1 folding, although in a general sense, the F_1 folding may have been essentially contemporaneous. Siltstone beds in the Beavertail Point phyllites near this contact have truncated cross-laminated ripples which indicate that it is facing north into the contact with the Dutch Island Harbor formation which is itself facing south into the contact. There are tiny, lenticular fragments of green phyllite breccia strung out in the dark phyllite within a few inches of this folded tectonic slide contact.

Follow the folded contact north to Station 1-10.

1-10. This station is at the junction of the slide contact with the Beavertail fault. Here in addition to relationships of 1-9, the Dutch Island Harbor formation is brought into contact with the Beavertail Point formation by movements along this well exposed post-F_2 fault along which the S_2 cleavage is offset.

Return to parking area and proceed S. to Stop 2 at Beavertail Point Lighthouse, Beavertail State Park Headquarters and Visitor Center.

Mileage

5.9 Park as near as possible to the Lighthouse, and to the historical marker at the foundation of the old Beavertail Lighthouse (Fig. 3).

Stop 2. Beavertail Point member, Dutch Island Harbor member, tectonic slide, and Beavertail fault. At Beavertail Point.

Features of general geological interest at this locality include:

A. Lithology and sedimentological features of the Beavertail Point member at the type locality, as described above in the text.

B. The tectonic slide at the contact of the Dutch Island Harbor formation and the Beavertail Point member noted above is well exposed here. This is essentially the same type of slide contact on the north side of the Beavertail fault as was observed at Stop 1, Station 1-10 on its south side. A well developed mylonite zone within the Dutch Island Harbor formation near but not at the contact may be seen.

C. Ichnofossils or "worm trails" are well developed here.

D. An F_1 fold may be observed as well as an excellent development of F_2 folds especially at the slide contact where the color contrast enhances the recognition of S_2 fold patterns.

E. Late faults showing several kinds of features or relationships.

A series of specific features may be examined at the following field stations (Fig. 6):

2-1. Well developed sedimentological features of the Beavertail Point member should be examined so that similarities and differences may be noted between that member and the Lion Head member, possibly a facies variant of the Beavertail Point member. These features are exposed in cross sections of F_2 folds to which the dominant S_2 cleavage is axial planar.

2-2. Southeast side of Beavertail fault. Gray and black phyllite beds within the Beavertail Point member are exposed.

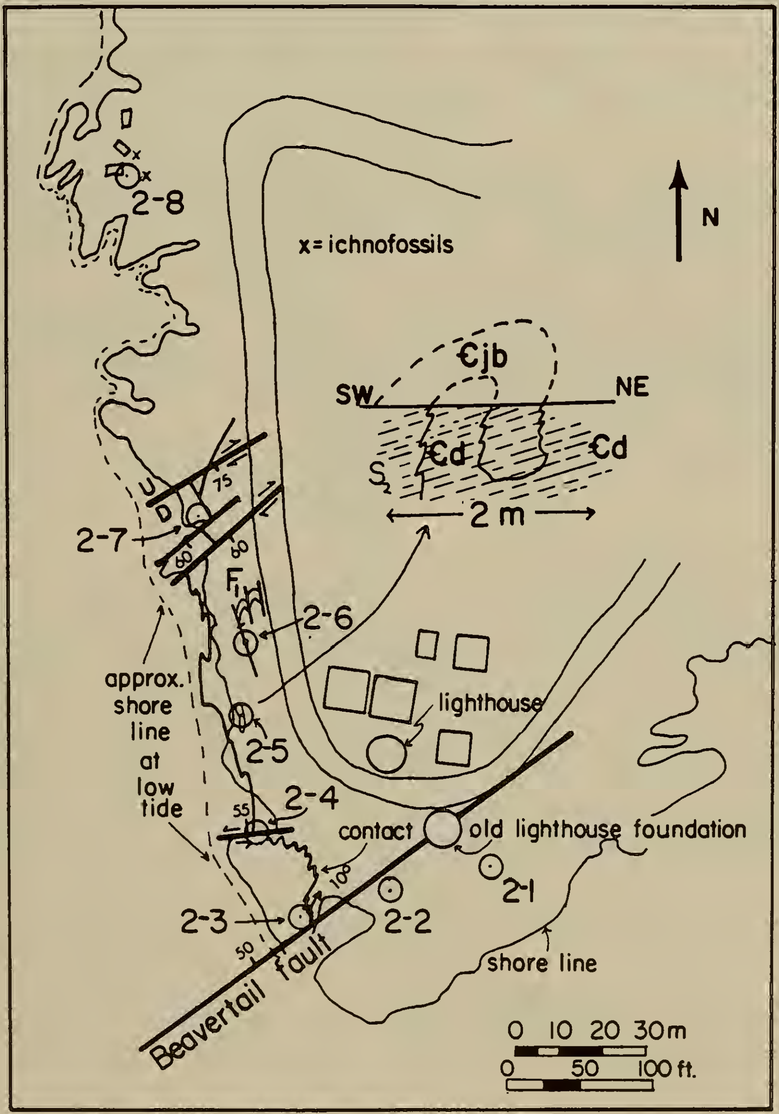

Figure 6. Location map for Stop 2 showing Beavertail fault, and slide contact, offset along late faults, and ichnofossil locality. Insert is a cross section of F_1 fold at 2-5. (Modified from Skehan and others, 1976).

2-3. The contact between the Dutch Island Harbor formation and the Beavertail Point member is well deformed by F_2 folds. This contact and the units on either side are offset by the adjacent Beavertail fault, a late post-F_2 fault. If interested in observing the folded contact walk it out as it climbs up and over a cliff (Fig. 6) looking for micro-breccia, truncated beds and other slide associated features which, however, are not as well developed here as at Stops 3, 4 and 5.

2-4. Late quartz-breccia filled fault (N. 87°E.; 55°NW) offsets the tectonic slide contact about 7 m in a sinistral sense.

2-5. An upright F_1 fold, which deforms the tectonic slide contact as indicated in Figure 6.

2-6. The bedding within the Dutch Island Harbor formation about 7 m east of that contact is intensely disrupted. Cutting through this point there is a 0.3 m thick mylonite zone N. 15°W.; vertical) which truncates bedding.

2-7. At this point the Dutch Island Harbor formation is in contact with disrupted, brecciated beds of a mass within the Beavertail Point member. Siltstone beds are deformed as upright F_1 folds N. 25°W.; 12°) plunging within this disrupted mass.

2-8. Worm trails or ichnofossils identified by Pickerell (written comm. to Logue, 1981) as Palaeophycus (= Buthrotrephis), Planolites, and Helminthopsis. These fossils are exposed on bedding planes where these are parallel to S_2 cleavage.

Return to parking area and proceed north on Beavertail Road.

Mileage

6.4	Turn left (west) on a road 30 m north of the first of two remaining U.S. Naval Communication installations of Fort Burnside (Fig. 3). Proceed west on this straight road toward the western shore. Please note that as this guide is being written and published the road system within the Park is in process of being developed. Thus the roads and route of best access to Stops 3 and 4, as described here, may differ from that which will be developed. However, we will locate the Stops as accurately as possible with reference to recognizable landmarks unlikely to change rapidly.
6.55	Dead end against a road approximately parallel to the shore. Go south. There are two signal towers just west of this road.
6.6	Park close to the second (more southerly) of these two towers. Follow the blocked-off road to the right (west). Two 10 inch posts stick above the brush. Stop 3 is located at the post at the clifftop.

Stop 3. Lion Head and Short Point members in slide contact with Beavertail Point member. Western shore of Beavertail at southern property limit of Fort Burnside.

Features of general geological interest include (Fig. 7):

A. The lower stratigraphic units seen at Stop 1, except for the Taylor Point member and a small section of phyllite interpreted as Beavertail Point member.

B. Excellent display of F_2 as well as some small F_1 folds. Axial planar S_2 cleavage is well developed here.

C. Truncation of beds of the Short Point member against chaotically broken rocks at the south end of this stop represents a tectonic slide feature that is well developed.

D. The siltstone component of the bedded section is well developed in the southern part of this stop; whereas it is poorly developed in the northern part.

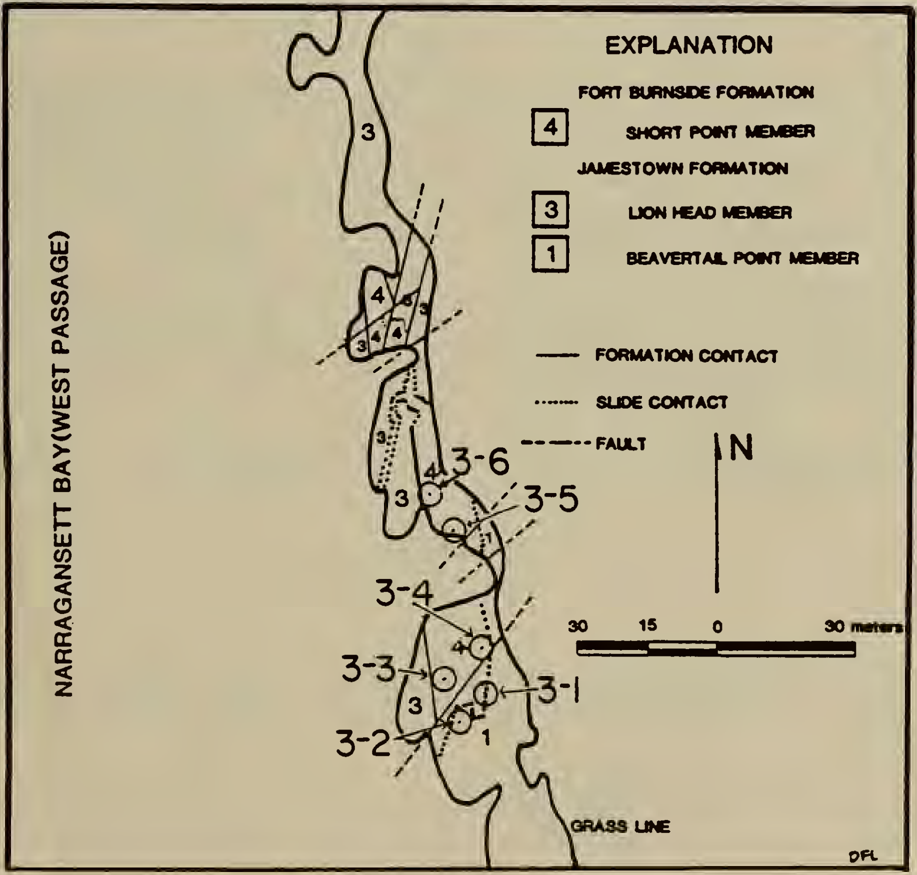

Figure 7. Geologic sketch map showing location of stations of Stop 3, western shore of Beavertail (Fig. 3).

Specific features may be noted at these stations (Fig. 7).

3-1. The phyllite has the dark gray color, massive appearance, trilobite fragments, and phosphate lenses typically associated with the Lion Head member. Although features diagnostic of differences between the Lion Head and Beavertail Point member are absent at this stop, these rocks are traced south into undoubted Beavertail Point member.

Along the northerly-trending steeply-dipping slide, there is a feature that appears to be characteristic of the slide contact in a number of locations. The phyllite near the contact weathers to a more finely divided phyllitic residue than is typically the case elsewhere, due possibly to a residual fabric produced in the sliding process.

3-2. The chaotic breccia is composed of Beavertail Point phyllite blocks and is especially well developed near its contact with adjacent chaotically deformed beds of the Short Point which are truncated abruptly at the EW contact (see C above).

3-3. Tops are consistently to the east in upward-fining cyclic sedimentational units, ranging from siltstone to phyllite, and on the "flame-like" features of the top of the dark phyllite units. Excellent cross sections of F_2 folds and S_2 cleavage seen here.

3-4. A thicker red-weathering siltstone bed outlines an F_2 fold.

3-5. From this point one may look south across the gorge and view the larger-scale F_2 fold with which previously noted features are associated. Note that the S_2 cleavage is more steeply dipping than the average at Stops 1 or 2.

3-6. Both limbs of an F_1 fold (N. 15° W. plunging at 25°) are cut by S_2 cleavage.

Return to vehicles. Turn around and return N.

Mileage	
6.7	Junction with access road over which we came to Stop 3. Bear right proceeding past parking lot on a road trending NE to meet Beavertail Road (Fig. 3).
6.9	Go left on Beavertail Road.
7.1	Beavertail Farm on right (east). Continue on Beavertail Road.
7.15	Turn to left (west). Pass second of the remaining buildings of Fort Burnside on north side of road, continuing on an unpaved road which trends generally W. toward the shore.

7.4 Road turns south just east of the brush-covered clifftop.

7.45 Parking on left. Access path to Stop 4 is 0.05 miles to the south.

<u>Stop 4</u>. <u>Tectonic slide contact</u>. West side of the western island, Beavertail State Park (Fig. 3).

Access is best accomplished near low tide when important relations at the south end can be most readily seen. This important outcrop is isolated by a rock-bound gully on the south and a secluded sandy beach and fairly steep seacliffs on the north, made so by the west-dipping 50° cleavage surfaces.

<u>4-1</u>. At the south end of the outcrop there is a well displayed cross section (Fig. 8A) of an F_2 fold. The lower slopes consist of Lion Head, the prominent fold is outlined by the Short Point member, and the upper slope is formed of Beavertail Point member. The Short Point member has tops indicators facing east into the slide contact. These include the siltstone fining upward and "flame-like" tops in the dark phyllite of the cyclical sequence. In the Beavertail Point member a buff siltstone bed (Fig. 8A) may be traced to the slide contact where it strikes into the contact.

<u>4-2</u>. Climb upon the outcrop following the slide contact for 10 m where the contact divides, the more westerly splay cutting across the beds of the Short Point member. The north-striking beds between the two slide surfaces and the small ramp folds at the contact (Fig. 8B) are well displayed in this oblique cross section.
The characteristic trilobite "hash" and phosphate lenses, common to both the Beavertail Point and the Lion Head members are present in the rock east of the slide. The presence of the red-weathering sandstone and the tracing of these rocks into more typical Beavertail Point rocks are the basis for the name of the unit.

Return to vehicles and retrace route to Beavertail Road.

<u>Mileage</u>

7.8 Turn left (north) on Beavertail Road (Fig. 3).

8.3 Park near the fire access road to Hull Cove, walk to the beach and turn left toward the brillant gray outcrops.

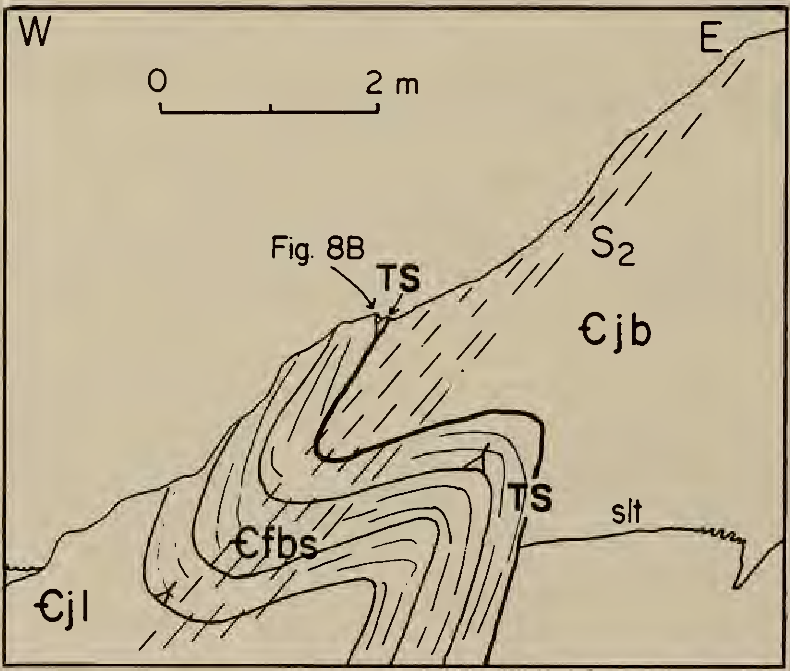

Figure 8A. Schematic cross section at south end of Stop 4 (Fig. 3) showing the tectonic slide contact (TS) between the Beavertail Point member (Ꞓjb) and the Short Point (Ꞓfbs) and the Lion Head (Ꞓjl) members. These are deformed by the F_2 fold and cleavage. Siltstone bed (slt) in Beavertail Point member is truncated at slide contact, and facing direction in the Short Point is toward the slide contact.

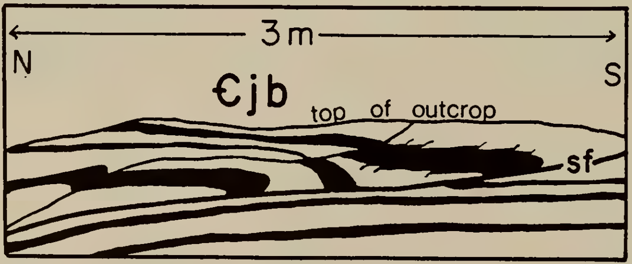

Figure 8B. Cross section sketch looking ENE at a splay of the main tectonic slide as exposed on the S_2 cleavage dipping toward the viewer and approximately 10° from the strike of the beds, illustrating apparent angular relations of beds at the plane of the slide. sf - splay fault; black - dark phyllite; white - gray phyllite except for Ꞓjb in background.

Stop 5. Hull Cove member at type locality in tectonic slide contact with other units including Short Point member at type locality. Hull Cove and Short Point (Fig. 9).

Features of general geological interest here include:

A. The Hull Cove and Short Point members of the Jamestown and Fort Burnside formations respectively at their type localities.

B. The tectonic slide breccia is very well displayed and it was here that it was first recognized as a pre-F_2 fault related feature.

C. The Dutch Island Harbor formation and other distinctive units are strongly deformed by late faulting.

Specific features may be observed at these stations:

5-1. The shoreline exposures of this distinctive unit display progressively the changes in lithology that are characteristic. Chalky white siltstone lenses and red-weathering siltstone beds are nearly flat-lying except where the dip locally is recognized as steepening in an F_2 fold. Tops indicators are few and difficult to recognize as diagnostic. S_2 cleavage strikes E and dips an average 10°N. Logue (Fig. 9) has found ichnofossils at this station.

5-2. West of the brown-weathering meta-minette dike. White phyllites contain red siltstones with cross lamination ripples; within 10 m of the dike the white siltstones increase in number and thickness; they are nearly flat-lying, north-dipping beds.

5-3. The minette dike (N. 60°W.; 50°NE) cuts the Hull Cove member, the brecciated slide contact and the adjacent Dutch Island Harbor formation, but is cut by the S_2 cleavage. There is well developed trilobite hash near the west end of the dike.

5-4. 30 m east of the western exposure of the dike the polymictic mylonitic breccia in a black matrix is well exposed 1 m above the dike's upper contact. Here it is clear that the breccia is exposed in tight S_2 folds and attains its greatest development of 0.3 m although the true thickness may be variable. You may trace the breccia discontinuously along the folded contact which, together with the dike, is cut by late normal faults with small (1.5 m) dextral displacement (Fig. 9). The breccia zone on average appears to strike N. 10°W. and is vertical. The Dutch Island Harbor formation is cut by numerous late faults which may be observed en route to 5.5.

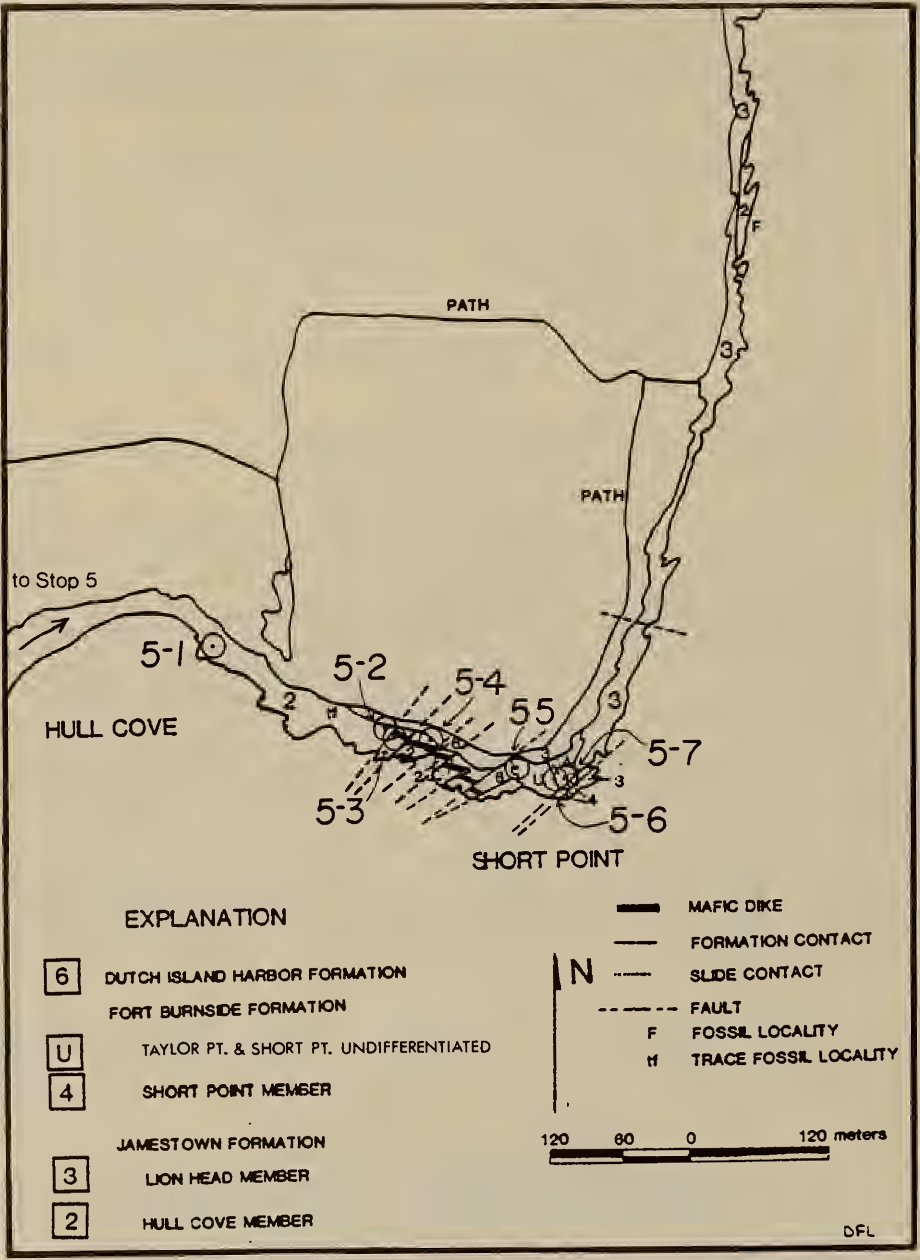

Figure 9. Geologic sketch map showing location of stations on traverse at Stop 5, Hull Cove and Short Point (Fig. 3).

5-5. The contact of the Dutch Island Harbor formation with the complexly deformed, in part undifferentiated Fort Burnside formation is well exposed at the type locality along the south facing cliffs of Short Point. The sequence is very well displayed as F_2 folds in an inverted succession which tops to the west into the slide contact. The tops indicators are upward fining graded beds, "flame-like" structure in the dark phyllite, and the cyclical sedimentation units. A variety of F_2 fold shapes and faulted folds may be observed in the sea cliff cross sections which are quite accessible.

5-6. Trilobite "hash" beds of the Lion Head member are seen on the south facing part of the Point.

5-7. Rounding the eastern side of the point blocks of Short Point member are exposed in several locations, the present exposure resulting from complex polyphase faulting, in part at least, late. Near the shore two blocks have moved relatively 10 m in a dextral sense along slickensided quartz-filled faults (N. 35°E.; 40°SE).

We will not proceed further north from Short Point but note that an infantile form of Paradoxides was found by one of us (D.F.L.) adjacent to the contact of the Hull Cove with the Lion Head member of the Jamestown formation (Fig. 9).

Return to vehicles and go N. on Beavertail Road.

Mileage

10.0 Park at the east end of Mackerel Cove Beach (Fig. 10). Walk southeast along the eastern shore of Mackerel Cove. Low tide conditions are helpful for best viewing of the succession. They are essential to shoreline access to the contact of the Cambrian beds with the Pennsylvanian Pondville formation at the southern end of the traverse.

Stop 6. Relationships of Lion Head and Hull Cove members; thrust fault relations of Pennsylvanian Pondville formation on Hull Cove. Eastern shore of Mackerel Cove.

Features of general geological interest include:

A. Relationships between the Hull Cove and the Lion Head suggest that the former is stratigraphically below the latter and therefore forms the base of the exposed Cambrian strata.

B. The dominant structure is a westward-facing F_2 fold. At the southern end of the traverse the Hull Cove member (Fig. 10) is cut by numerous NE-striking, SE-dipping thrust faults. The Newport granite and the overlying basal Pennsylvanian Pondville formation have been thrust as a unit onto Cambrian rocks. Kay and Chapple (1976, p. 438) identified this fault but considered it as within the Pennsylvanian as rocks to the north (Hull Cove member) were then considered to belong to the Rhode Island formation.

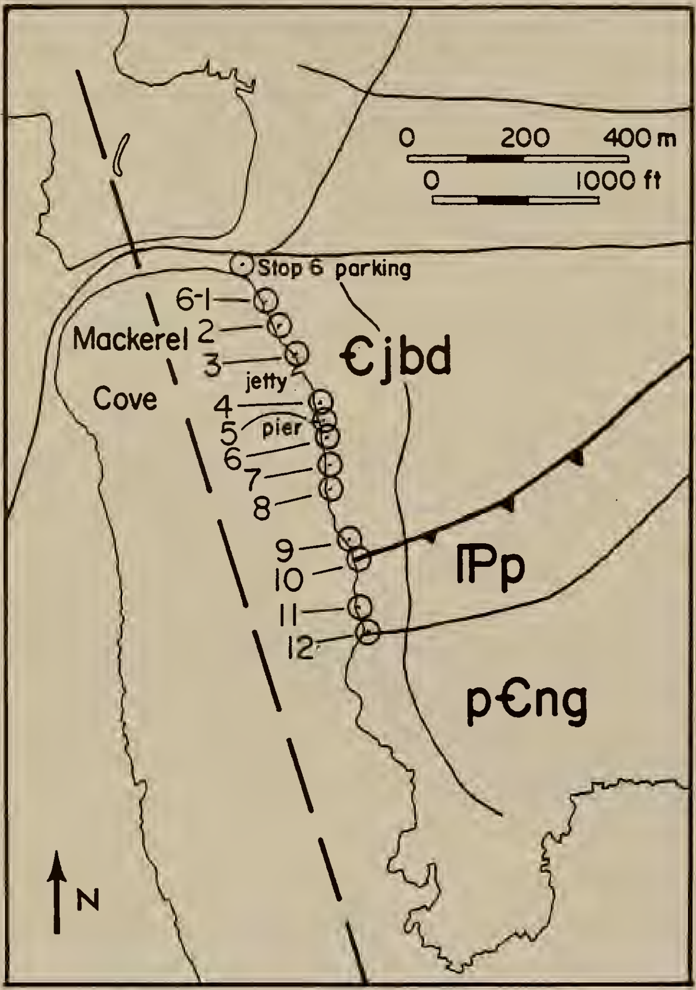

Figure 10. Location map for traverse south (Stop 6) along the eastern shore of Mackerel Cove, Conanicut Island.

Specific features may be seen at the following stations (Fig. 10):

6-1. About 150 m S. of Mackerel Cove Beach are outcrops of inverted Short Point member (N-S; 45°E) which face to the W in an F_2 fold (S_2 cleavage - E-W; 25°- 45°N.)

6-2. Contact of Short Point with Lion Head which is non-porphyroblastic. F_2 fold plunges 10° toward N. 12° W. The folded contact is well exposed north of a former jetty now consisting of a line of rock blocks and metal pipes.

6-3. Lion Head, coarsely porphyroblastic and lineated (N. 65°W.; variable plunge) on S_2 cleavage, is cut by late fault consisting of a 0.5 m thick gouge and vein-quartz.

6-4. About 80 m south of the jetty (6-2) is the covered contact between the Lion Head and the Hull Cove members, both well exposed nearby. The Hull Cove beds, as was the case with the units to the north, strike in a northerly direction, dip gently E, and are inverted in an F_2 fold whose beds face to the west.

6-5. North of and at the boat pier are exposures of fossiliferous Hull Cove member. S_2 cleavage is warped by kink bands (N. 35°E.; 80°SE.) whose short limbs step down to the SE.

6-6. 70 m S. of the pier (6-5). Reverse fault (N. 50°E.; 60°SE) brings Hull Cove beds south of the fault against Lion Head beds.

6-7. 70 m further S. is the contact between the inverted west-facing Hull Cove beds (NS; 20°E) which go up into the massive dark phyllite of the Lion Head member. Thus it appears that the stratigraphic relations of these two members of the Jamestown formation are established.

6-8. Southward from this station at a fault (N. 80°E.; 50°SE), the Hull Cove beds are cut by numerous high angle reverse faults. The cleavage orientations are disrupted and irregular quartz veins are abundant.

6-9. Several NE- and ENE-striking thrust and high angle reverse faults indicate that the influence of the Jamestown thrust fault is more intense (Fig. 10). A meta-minette dike, rusty weathering, is involved in faulted folds which are overturned to the NW. At its northern exposure, about 40 m N. of the main thrust fault the dike contact with Hull Cove beds is N. 55°E.; 60°SE.

6-10. The Jamestown thrust fault (Fig. 10) has transported the Pennsylvanian Pondville conglomerate and its underlying Newport granite northwesterly onto the Middle Cambrian. These relationships, which persist to the eastern shore south of the village of Jamestown, however, are not present on the western island. Thus we infer the presence of the Mackerel Cove fault, having sinistral motion, and interpret that it is responsible for transporting this mass of rocks of the southern part of the eastern island to their present positions relative to the Cambrian of the western island.

Retrace steps to vehicles. End of field trip for this year!

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ALLEGHANIAN DEFORMATION AND METAMORPHISM OF SOUTHERN NARRAGANSETT BASIN

R. Burks[1], S. Mosher[1], and D. Murray[2]

[1]Dept. of Geological Sciences, The Univ. of Texas at Austin, Austin, TA 78712
[2]Dept. of Geology , Boston University, Boston, MA 02215

INTRODUCTION

The Narragansett Basin of southeastern Massachusetts and eastern Rhode Island is an arcuate structural basin, having a northeast-southwest trend in Massachusetts and north-south trend in Rhode Island (Fig. 1). It consists of up to 3700 meters of Pennsylvanian to Permian-aged nonmarine clastic sediments. The basin is structurally defined by the effects of the Alleghanian deformation, and its present shape may have an imprecise relationship to the Late Paleozoic sedimentary environment in which the rocks accumulated.

Several horsts of granitic basement occur within the basin, and recent offshore geophysical studies suggest that the Narragansett Basin plus several of these horst blocks extend at least 32 kilometers southward under Long Island Sound (McMaster and others, 1980). Gravity traverses across the Basin (Skehan and Murray, 1979) indicate an irregular basin/basement interface that in parts of the northern section of the Basin is at least 3300 meters deep. Upublished gravity traverses, field work, and drilling also show that the basin extends to the northeast at least to coast.

Permian-aged (Murray & Skehan, 1979, p.15) deformation and metamorphism increase to the south, culminating in multiple episodes of folding and upper amphibolite facies metamorphism (Fig. 2). The S-type Narragansett Pier granite intrudes the southwestern margin of the basin. More detailed discussions of the geology of the basin are given in Quinn (1971), Quinn and Moore (1968), Skehan and others (1976), articles in Cameron (ed. 1979), Murray and Skehan (1979), and Skehan and Murray (p. 1-14, in Skehan and others, 1979).

TECTONIC SETTING

The southwestern extensions of two distinct European foldbelts, the early Paleozoic Caledonian (Taconic + Acadian equivalent) and the late Paleozoic Hercynian or Variscan (Alleghanian), merge in New England to form the Applachians. The Pennsylvanian-age Narrgansett Basin has been affected only by the Alleghenian orogeny and is therefore the key to determining the nature and amount of late Paleozoic overprint on the older rocks. The formation of the basin itself is believed to be either the consequence of rather localized brittle tectonics (Webb, 1969, MacMaster and others, 1980), or the result of the closure of a Hercynian ocean during the collision of eastern North America with either northwestern South America or Africa (Rast and Grant, 1973; Murray and others, 1978; Skehan and Murray, 1980a,b; Snoke and others, 1980; Pique, 1981; Rast, 1981).

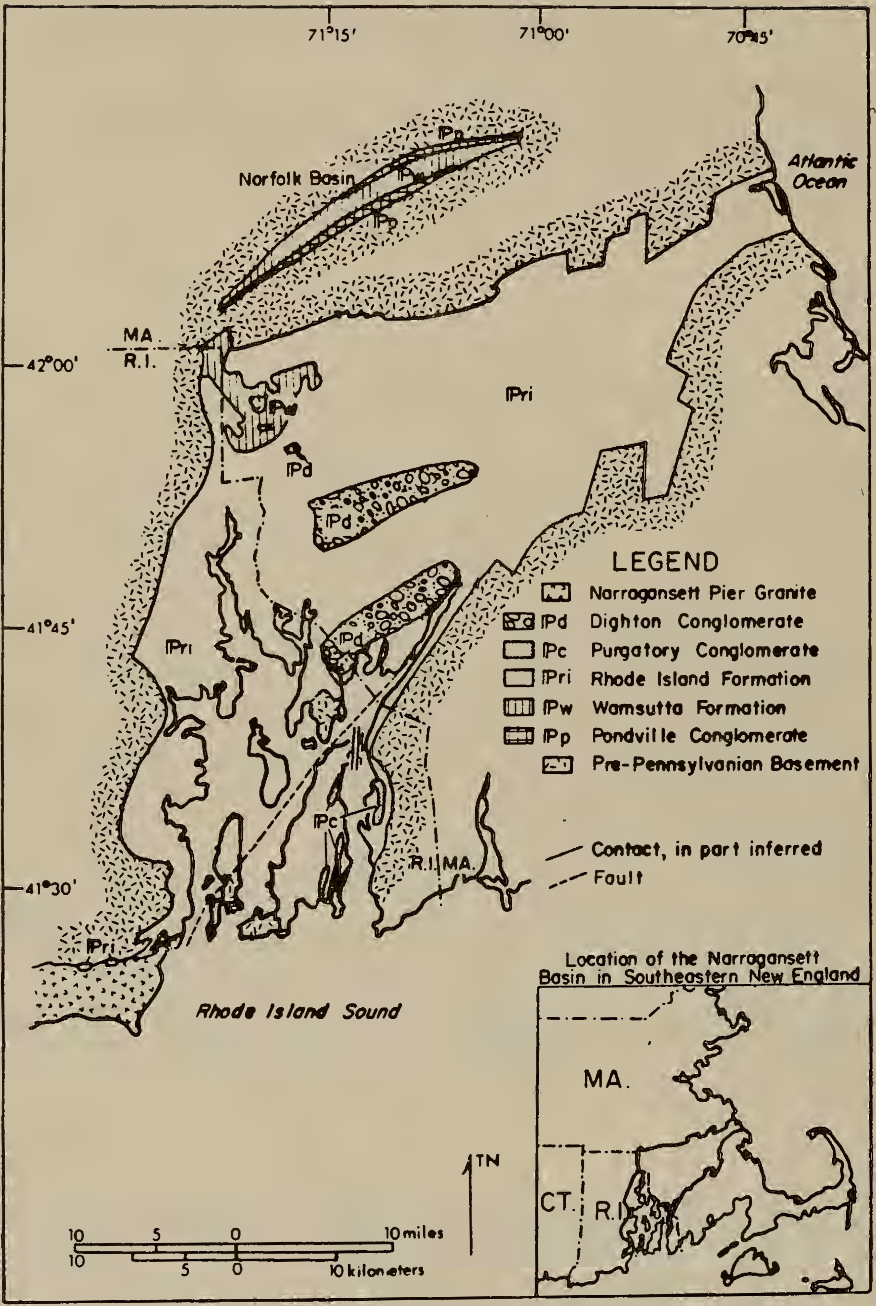

Figure 1. Geologic map of the Narragansett Basin, southeastern New England. Compiled from Quinn & Moore (1968) and Murray & Skehan (1979)

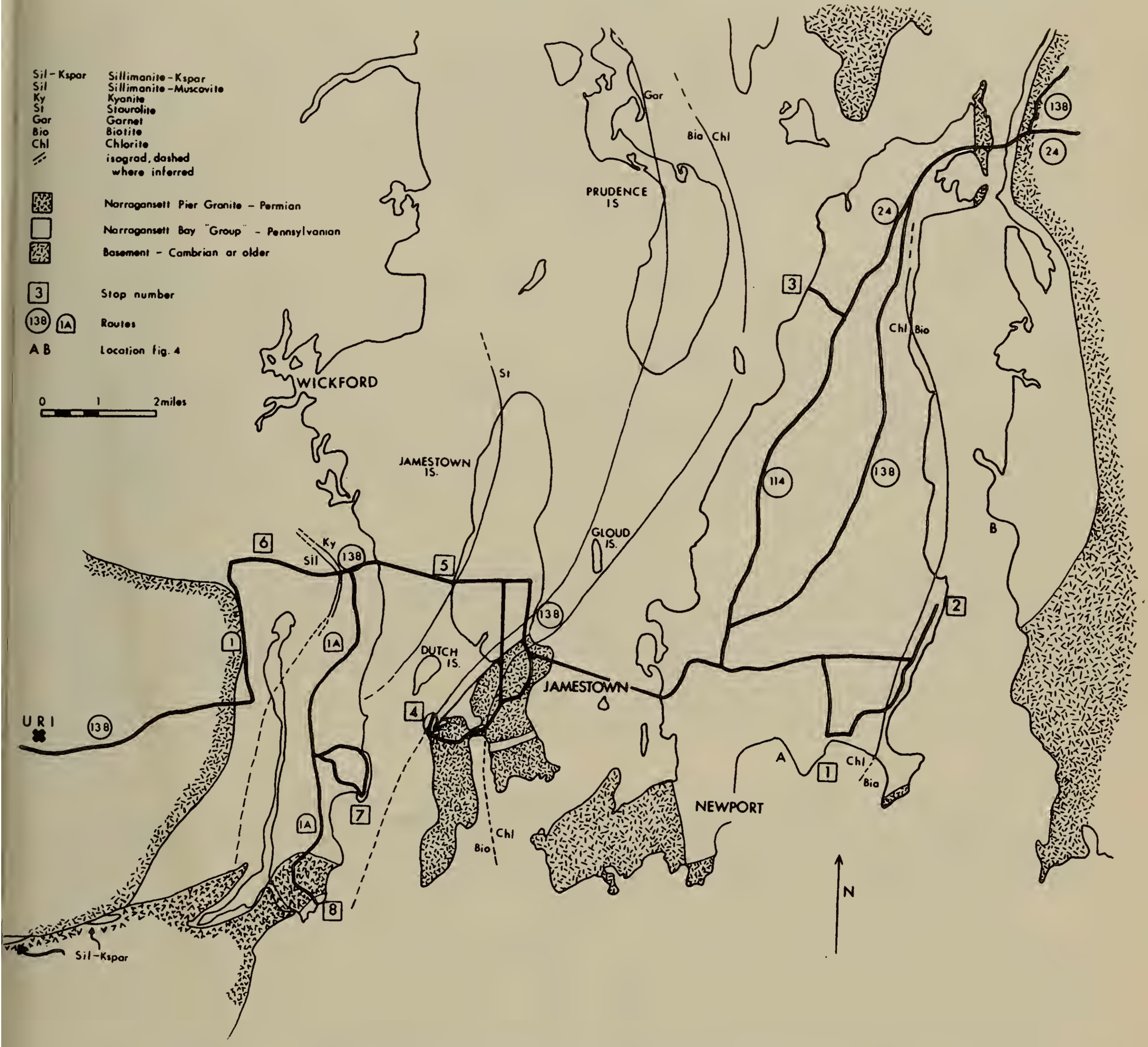

Figure 2. Southern Narragansett Basin, Rhode Island
Isograds compiled from Quinn (1971), Grew & Day (1972),
Murray & Skehan (1979), Mosher (1980), and Thomas (1981)

STRATIGRAPHY

Five formations, now referred to collectively as the Narragansett Bay"Group" (Skehan and others, 1979) are recognized, and their probable stratigraphic relationships are shown in Figure 2 of Murray and others (this volume). The lowest formation, the Pondville, is a basal conglomerate at the northern and western basin margins and an arkose at the southern and eastern margins. In the north the Pondville is overlain be the Wamsutta Formation. The latter consists of reddish siltstones and fine grey sandstones, together with coarser channel deposits. Volcanic detritus is widespread and both silicic and mafic lava flows occur near Attleboro, Massachusetts (Mutch, 1968).

In the southern part of the basin the Pondville is overlain by the Rhode Island Formation which in the north interfingers with and overlies the Wamsutta Formation. The Rhode Island Formation is by far the thickest unit in the basin and has extensive and well documented megafora (Lyons 1979) that indicate sedimentation occurred from 310 to 290 m.y. The formation consists of sandstone, siltstone, conglomerate, shale and coal. The lowest unit in contact with the Pondville is usually a black carbonaceous shale. The unit is cut by numerous lensoid channels composed of coarse sands, gravel and conglomerate, and typically is overlain by a micaceous siltstone. Massive boulder and cobble conglomerates, the Purgatory and Dighton, interfinger with the upper part of the Rhode Island Formation.

The stratigraphic and sedimentary relationships suggest that horst blocks were bounded by humid alluvial fans and that basinward from these fans, highly vegetated floodplains were traversed by meandering to anastomosing streams. Deposition was probably rapid and at least locally synorogenic (Skehan and others, 1979; Severson and Boothroyd, 1981).

STRUCTURE

The major structural trends within the basin follow that of the basin itself, trending ENE in the northern portion of the basin and nearly NS in the southern portion. In the north only one main deformation has affected the rocks whereas in the south evidence for multiple deformations is found.

In the south the most intensely and complexly deformed rocks form a north-east trending zone parallel to the Beaverhead Fault. (This zone contains Bonnet Shores, Beaverhead, Dutch Island, Gould Island, and the northwest shore of Portsmouth near Stop 3). The intensity, but not the complexity, of the deformation decreases outwards in both directions from this zone and is least evident in the massive Purgatory Conglomerate to the southeast. The entire basin is cut by numerous high angle faults which are both syn- and post-folding events; both normal and reverse movements are evident and large offsets are common.

Within the most intensely deformed zone at least three phases of Alleghanian deformation are preserved (Fig. 3). An early isoclinal folding (F1) produces the dominant layer-parallel foliation (S1). Generally, F1 trends N10E with S1 dipping SE. The second event to affect these rocks is a nearly coaxial folding (F2) with axial planes at a high angle to that of the earlier folds. Usually the F2 folds are relatively minor with low amplitudes, however, in places they become more pronounced, with amplitudes of several meters. A west dipping crenulation cleavage (S2) is often associated with them. A third folding (F3) formed large amplitude folds (up to several meters) that trend approximately EW. In places an axial planar crenulation cleavage (S3) is observed. The rocks have also undergone a late stage NS extension which caused large scale boudinage and normal faulting. The boudinage caused broad EW trending warps of all S surfaces and earlier fold axes on both outcrop and regional scales. The high and low angle normal faults reorient preexisting fold axes as well as cause drag folding. (The NS extensional features are best exposed on Gould Island, a Navy base with limited access.) At some localities within the zone several generations of nearly coaxial but cross-cutting crenulations of S1 are observed which formed prior to the EW trending, F3 folds.

Southeast (most of Aquidneck Island and the eastern basin margin; Mosher, 1978; Farrens, pers. comm., 1981) and northwest (Conanicut, Prudence, Hope, and Hog Islands (Thomas, 1981) and the western basin margin) of this zone the dominant structure is the first, N10E trending isoclinal folds (F1) with a well developed axial planar schistosity (S1). The second deformation is commonly expressed as a crenulation cleavage (S2) and warping of S1. The third, EW trending folds (F3) and an associated schistosity (S3) are sporadically developed. Kink bands and boudinage (NS extension) are ubiquitous throughout the southern basin. The orientations and geometric relationships of the structures are similar to those seen in the more intense zone (Thomas, 1981; Farrens, pers. comm., 1981).

Further southeast where the massive Purgatory Conglomerate crops out (southern Aquidneck Island) the major structure is a series of tight upright to overturned folds (F1) with variable vergence which again trend N10E (Mosher, 1980a). Cleavage is everywhere axial planar. North-south striking thrust faults cut the limbs of the oveturned folds and show the same direction of tectonic transport (Fig. 4). These faults cause extensive cobble deformation for a distance of 3m from the fault plane (Mosher, 1980b). Evidence for later deformations include a second sporadically developed cleavage, kinkbands, large scale boudinage indicating north-south extenstion and minor folding of eastward dipping thrust faults.

Much of the variation in deformation intensity in the southern portion of the basin can be attributed to competency differences. The massive Purgatory Conglomerate and all channel sands are the least affected by the deformations and the black carbonaceeous schists the most deformed. There is, however, a pronounced increase in intensity for all rock types near the Beaverhead fault.

METAMORPHISM

The dominant thermal event in southeastern New England is a Barrovian metamorphism that reached upper amphibolite facies conditions in the vicinity of Stop 6 (Stook Hill). The Beaverhead fault probably truncates the isograds, although the offset may not be large. Although the thermal maxima is very roughly centered about the contact of the metasediments with the Narragansett Pier granite, in detail the granite appears to truncate isograds, and at Cormorant Point (Stop 8) the regional metamorphism prior to granite emplacement attained only garnet grade. Thus, the "bullseye" pattern of the isograds shown centered about the southwestern margin of the basin on previous maps (Quinn, 1971) may be an artifact of the sample base. Peak metamorphic conditions, based upon mineral assemblages (Grew and Day, 1972) and chemistry (Murray, unpub. data), suggest conditions of $T=600^{\circ}C$ and $P=5$ kbar at Stook Hill and vicinity.

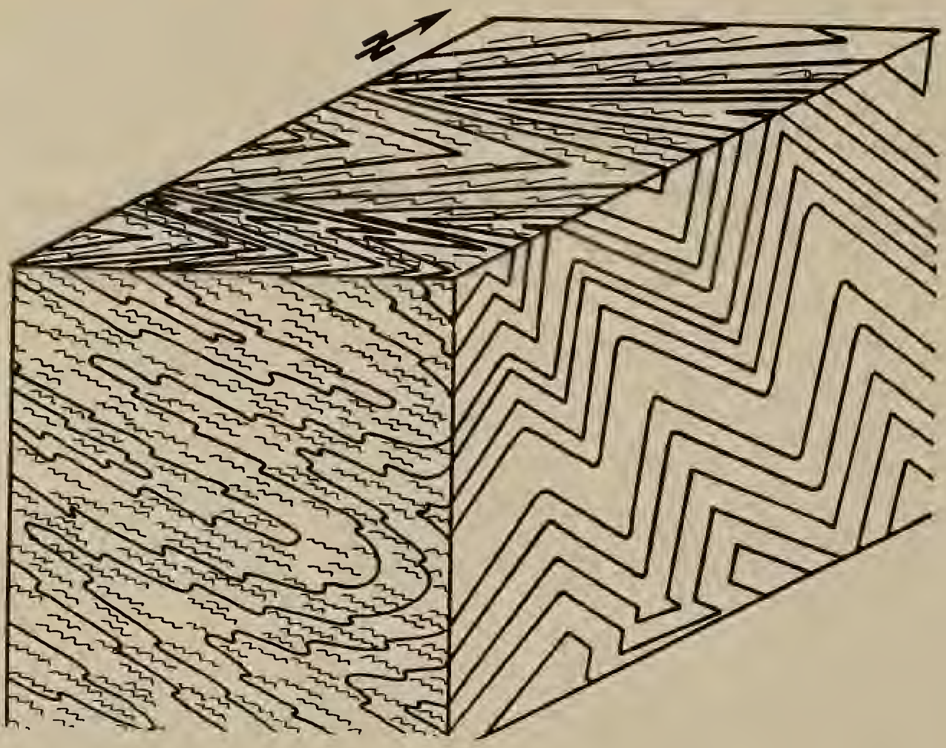

Figure 3. Diagrammatic representation of three major episodes of folding in southern Narragansett Basin. D1 is NNE trending and characterized by east-dipping axial planes. D2 is roughly coaxial with D1, has west-dipping axial planes, and occurs on a smaller scale. D3 is E-W trending and chevron in style.

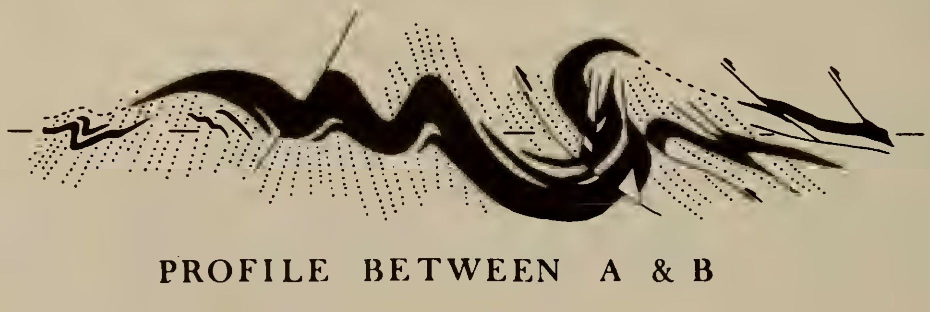

Figure 4. Structural profile across southeastern Narragansett Basin. The black bands represent the Purgatory Conglomerate. From Mosher, 1978. The location of the profile is given on Figure 2.

Illite crystallinity (Hepburn and Rehmer, this volume) and coal petrology (Murray and Raben, 1980, and Murray and others, this volume) indicate that $T<300^{\circ}C$ for the northwestern part of the basin.

Metamorphic and deformational intensity do not strictly correlate (Fig. 5), and detailed petrographic analysis has been done so as to determine the relation between these two parameters (Burks, Farrens, Mosher, Murray, Thomas, Wiechmann, Wintsch). The major metamorphic event was contemporaneous to slightly younger than the main period (D1) of folding, and a widespread retrograde metamorphism followed the third episode of folding (Murray & Skehan, 1979; Burks, 1981). During the first phase of folding pressure solution was the primary deformation mechanism responsible for the S1 cleavage, occurring at relatively low temperatures (Mosher, 1978, 1980a). The first metamorphism peaked slightly after the first deformation at Beaverhead, and progressively younger than it to the north and west (Fig. 5).

In the fine grained rocks the closely spaced primary layering was also crenulated. Initial deformation of coals caused degassing of methane and brecciation. Precipitation of graphite, because of increasing temperature and/or oxidation of the released gas by surrounding sediments, coated brecciated coal fragments and defined cleavages in surrounding sediments (Murray & Raben, 1980). Concurrently, fibrous quartz±mica veins developed in the brecciated coals (Stop 3). Many of the structural and petrologic details of these rocks may be explained in terms of the interaction during progressive metamorphism of mechanically and chemically contrasting materials (e.g. coal and rock), and the topic is explored more fully in another field trip (Murray and others, this volume). The second, less intense deformation that produced a crenulation cleavage at a high angle to the pervasive S1 schistosity, was not accompanied by metamorphism at Beaverhead or Southern Prudence Island.

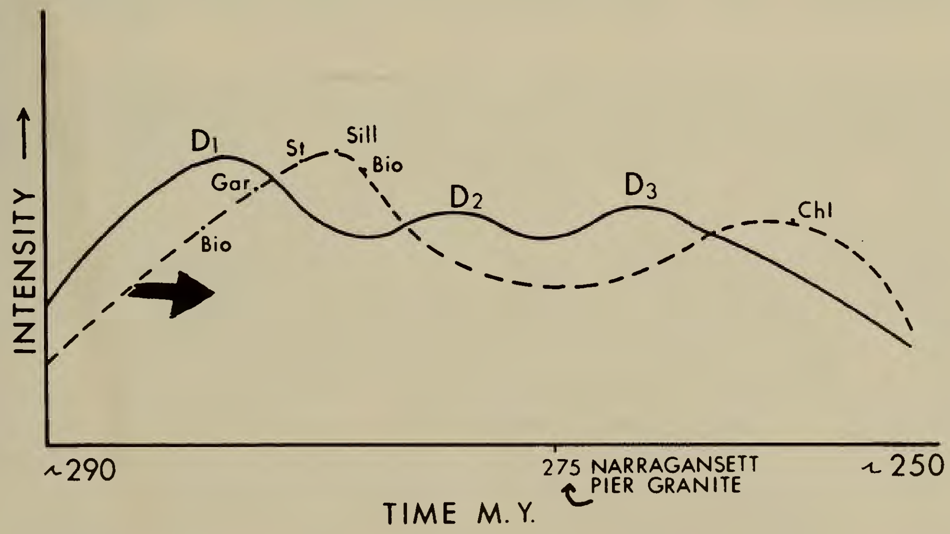

Figure 5. Relationship between metamorphism and deformation for the southern Narragansett Basin. The arrow shows the relative change in the relationship going NE towards Prudence Island.

However, the first metamorphism occurred synchronously with the F2 in the northern part of Prudence Island (Thomas and Mosher, in prep.). The third event was most intense in the Beaverhead area, and was not accompanied by growth of metamorphic minerals. Retrograde metamorphism occurred after the third deformational event, as chlorite replacing porphyroblasts near S3 crenulations is randomly oriented and undeformed. The distribution of this second metamorphism does not simply correlate with any of the major structural features (i.e. Beaverhead fault), and the significance of its ubiquitous presence throughout the southern Narragansett Bay area represents one of the major unanswered questions.

The Narragansett Pier granite is a typical peraluminous (S-type) granite that has superimposed essentially no contact metamorphic effect upon the sediments. At Stop 8, except for regularly spaced joints, mineralized fractures, and deformation directly related to intrusion, the granite is uneffected by the metamorphic or deformational events that are recorded in the adjacent metasediments. However, a variety of deformation features (i.e. density of fracture cleavage, preferred orientation of microtextures, etc.) become increasingly well developed to the north of Stop 8. Recent work (Hermes and others, this volume; Kocis and others, 1978; Murray and S. Schwartz, unpub. data) has pointed out the critical role of this granite in our understanding of the Alleghanian orogeny, and the reader is referred to Hermes and others (this volume) for further discussions of the topic.

Until recently it was generally assumed that the metamorphism recorded in the Narragansett Basin was a fairly localized, and hence unimportant phenomena. A number of studies in the last few years, however, have shown that the Alleghanian thermal overprint upon southern New England is more pervasive and intense than previously realized (Day, and others, 1980; Dallmeyer, 1981; Skehan and Murray, 1980).

SUMMARY

Pennsylvanian rocks record three major episodes of folding accompanied by faulting, and locally additional phases (i.e. Stop 4 and Stop 7) may be recognized. One, and in many places two thermal events are seen. Studies of pressure solution phenomena and coal petrography imply that the first metamorphism began after the first (and most intense) episode of folding was underway. Moreover, the second, retrograde metamorphism occurred largely after the last period of folding. Incremental argon ages on metasediments and contiguous basement rocks (Dallmeyer, 1981) indcate that cooling and uplift took place by 235-250 m.y. These uplift ages, together with other radiometric and paleobotanical ages (see Murray and Skehan, 1979 for discussion) allow the Allgehanian orogeny to be unusually pecisely defined. Adjacent pre-Pennsylvanian rocks show many similar structures and geometric relationships between structural elements to those in the Pennsylvanian rocks. The possibility then arises that only one (or perhaps no) deformation present in the pre-Pennsylvanian rocks occurred prior to the Alleghanian event. Alternatively, the similarities may be fortuitous and the pre-Pennsylvanian rocks were uneffected by any Alleghanian deformation. There is clearly a metamorphic difference as the pre-Pennsylvanian rocks within the Basin are uniformly of low metamorphic grade as opposed to the higher grade of the Pennsylvanian rocks. The nature and complexity of the Alleghanian deformation must be considered in any explanations of the late Paleozoic suturing of the Avalonian basement with southeastern New England.

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STOPS

MILEAGE	
	Leave Kingston on Rte. 138 East. Go 4 miles and turn north (left) onto Rte. 1. Go approximately 2.5 miles and take Exit for Rte. 138 East to Jamestown and Newport. Stay on Rte. 138, following signs for the Newport Bridge. Cross the Jamestown Bridge and follow Rte. 138 to the Newport Bridge (toll of $2). After crossing the bridge, take the Rte. 138 exit (the second one). The exit ramp ends at a stop sign across from Jai Lai (Hi Li). Turn right; log starts from this stop sign.
0.0	Hi Li parking lot.
0.1	On your left is Miantonomi Park; the road cuts are partially out of place and cut by numerous high angle faults. In the park underneath the tower are excellent exposures of Purgatory conglomerate which contains relatively undeformed cobbles.
0.4	Stop light for Rte. 114; go straight.
0.9	Go down steep hill to stop sign; go straight; most oncoming traffic will cut in front of you. The Easton's Pond is to the right. The pond is presumeably parallel to a major NS-trending fault which brings up the Newport neck horst.
1.0	Stop light for Rte. 214; go straight.
1.3	Stop light for Rte. 138A; continue straight. You are driving across a broad, eastward verging anticline which is exposed along the coast at Easton's point.
2.0	Turn right at base of hill onto Paradise Avenue. You are driving along the limb of an upright (F1) fold; Purgatory Conglomerate outcrops to your left.
2.5	Small road to your left goes to the Paradise Quarry, the best place to find good samples of Purgatory Conglomerate. Permission can be obtained at the office.
3.4	Bear to right at the Y intersection and park in the beach parking lot to your left. (The parking lot is before the hill.)

STOP 1

Purgatory Chasm State Park. (No hammers) This is the classical outcrop of Purgatory Conglomerate used to demonstrate the nature of the 'stretched' cobble conglomerate. The cobbles, however, have been deformed only by pressure solution and intercobble rotation (Mosher, 1978, 1980). The latter religned the already elliptical sedimentary cobbles so that long/intermediate axis plane is roughly parallel to the fold axial planes and the the long axes parallel the fold axes. Axial ratios of these prolate cobbles are 1/0.57/0.38 (Mosher, 1978; Mosher and Wood, in prep).

Large indentations and planar contacts are observed between quartzite cobbles, and long fibrous quartz pressure shadows are observed at the long axis terminations of the cobbles. The matrix between the cobbles is a mica- and heavy mineral-rich selvage left behind as a residuum after pressure solution. No evidence for internal penetrative cobble deformation has been found (Mosher, 1980).

This outcrop is located on the limb of an upright (F1) fold (Fig. 4). Bedding strikes approximately N10E and dips 55SE. At the top of the hill near the small parking lot for the Chasm, matrix beds grade into the Rhode Island Formation proper. These show cross-bedding and both a flat-lying and a steep cleavage. A high angle fault (N15E, 46NW) cuts across the chasm and can be traced for 1.2 km.

Coming out of the parking lot turn to your right and drive along the road which follows the beach. Between here and the next turn, you cross the axial trace of two synclines and an anticline.
3.7 Small hill on your left is a diabase dike.
Turn left onto Hanging Rock Road (first road). The ridge to the left is the southern end of one of the longest continuous exposures of Purgatory Conglomerate. This area is part of the Norman Bird Sanctuary and permission must by obtained at the main entrance on Third beach road.
3.9 Stop sign at intersection with Third Beach road. Go straight (road becames Indian Ave.). To the right of this road is an overturned limb of a syncline which is exposed along the coast.
5.5 Stop sign at intersection of Green End Ave. Go straight.
6.0 Stop sign at intersection of Peckham Lane. Go straight past Old Mill Lane.
6.6 Park along side of the road.

STOP 2

(Private property; not normally accessible, and in any case, must have permission). Purgatory Conglomerate on overturned limb of a westward verging anticline (F1). A NS trending, east dipping thrust fault cuts the conglomerate causing intense deformation for a zone approximately 6 meters wide. The center of this zone is filled with a 1 m wide quartz vein, and the sheared conglomerate has been mineralized (possibly with elemental sulphur), presumably from the degasification of the coals. The quartz vein and fault plane are curved suggesting latter backfolding of the thrust. This curved effect is better exposed along the same fault further to the north.

Cobbles within the intensely deformed zone are oblate (axial ratios 1/0.5/0.2) and the plane containing the long and intermediate axes parallel the fault plane. Cobbles away from zones are prolate (axial ratios 1/0.48/0.3). All cobbles were deformed by pressure solution, however, within the zone some penetrative intragranular flow and fracturing has accompanied the pressure solution (Mosher, 1980, 1981).
Turn around and retrace route to Green End Ave.
7.7 Turn right on Green End Avenue. You will again cross most of the cross section in Figure 4. Exposures are in fields and the basements of many house Continue straight through two stop lights.
10.3 Bear to right and go up the hill.
10.8 Stop light for Rte. 138 and 114; turn right and follow Rte. 114 through 3 stop lights.
17.3 Turn left onto Cory Lane (first left after flashing yellow light), following signs for Portsmouth Abbey School.
17.9 Bear right after the Portsmouth Abbey Hockey Rink, and continue into the school's parking lot. Path leads down to boathouse on shore.

STOP 3
Shoreline exposures of Rhode Island Formation, northwest Aquidneck

Island. Nearly continuous outcrops of fossilerous slate, siltstone, sandstone, and coal occur both north and south of the Abbey boathouse. Approximately a kilometer to the north can be seen the rectangular tower of the Kaiser Aluminum plant, which was built over the northern (of two) shafts of the Portsmouth coal mines. The historical and geological relationships of the coal seams are covered elswehere in this volume (Murray and others).

Sedimentologically, the rocks are finer grained than most of of the Rhode Island Formation seen elsewhere, and they may represent either lacrustrine or floodplain deposits. A well-developed floral assemblage from the middle of the strip of outcrop north of the boathouse indicates that the sediments are Westphalian D or Stephanian A in age (Fig. 2 in Murray and others, this volume). Coal petrography (Murray and others, this volume) and illite crystallinity studies (Rehmer and Hepburn, this volume) coupled with routine petrography suggests temperatures $T=400^{\circ}C$ were attained during metamorphism.

Both strips of outcrops are characterized by N20E 30SE subparallel bedding and cleavage, with the cleavage being axial planar to tight F1 folds. These folds are best displayed at the northern end of the northern outcrop. Two crenulation cleavages are sporadically developed; an earlier NE trending one, cut by a NNE trending crenulation. Open, E-W trending folds are cut by NE striking, NW directed thrusts at the southern outcrop. Pressure solution phenomena are well developed, and of particular interest are fibrous quartz-mica veins that formed in coal and carbonaceous slates.

Turn to left when leaving the parking lot and retrace route to Rte. 114.

18.5 Turn left and follow Rte. 114 through three lights.

25.0 Turn right onto Rte. 138 following Newport Bridge and U.S. Naval Hospital signs.

25.7 Pass Hi Li and turn left at sign for Rte. 138, Jamestown, New York, and the Newport Bridge.

25.9 Bear to the right following Rte. 138. When crossing the bridge, the coast to your right is Coaster's Harbor Island, a Navy base, where the Purgatory Conglomerate is exposed and cobbles show little to no deformation. The coast to your left is pre-Pennsylvanian as are the first two islands. As you approach the top of the bridge, the island to your right is Gould.

29.7 Pay toll and take exit to your right, in order to take the bridge west to Jamestown. Bypass the center of Jamestown, by continueing west on Rte. 138 to intersection with Main Road at stop light.

31.2 Go south (left) on North Main Road crossing Narragansett Avenue in Jamestown. Continue south to beach at Mackeral Cove (place where road passes over narrow sand spit. Immediately southwest of the beach the road becomes Beavertail Road; take the first right (west) onto Fort Getty Road. Proceed past the Fort Getty campground to the docking area, keeping always to the right on the unpaved roads. In summer there is a fee for entrance into this picnic and camping area. The stop consists of shoreline outcrops that begin about a thirty meters west of the dock.

STOP 4

32.2 Beaverhead (Burks, 1981). The earliest episode of deformation observable in these rocks is isoclinal folding about NNE axes which produces the dominant SE dipping schistosity (S1) seen throughout this area. This axial planar schistosity is multiply folded. Second generation small amplitude folds and crenulations have NW axes, and large EW trending chevrons and box folds represent the third phase of folding. Kink bands are nearly parallel to F3 folds and are presumeably late structures.

From parking lot, go up road toward pier, then about 60 meters west along beach. The pervasive schistosity (S1) strikes NNE and dips moderately to the SE. Lineations on the S1 are due to a well-developed crenulation cleavage (S2) that strikes NNW and dips moderately to the SW. A few meters down the coast, F1 folds are visible around sandy layers which show transposed bedding. Tight F2 folds trending WNW bend S1; open F3 folds trending ENE also fold S1 and S2. At the next rock protrusion S1 surfaces are warped by roughly EW F3 folds. The S2 crenulation cleavage is well-developed in the more schistose layers and can be seen in places folded by small F3 folds.

Return to the top of the seacliffs, either by retracing your steps or going up the broad rock face. Go down a few meters and take either the first or second steep path. At the base of the first path, large (EW trending, SE plunging) F3 chevron folds and numerous faults complicate the structural pattern of these carbonaceous schists. This outcrop is separated from the rocks of the previous stop by a NE-striking low angle fault. Conjugate kinks, or box folds, are prevalent folding a rarely visible S2. Several thin isoclinally-folded pyrite-replaced layers are visible. At the base of the second path are similar structures. In addition, highly foliated Pondville arkose is exposed indicating that this outcrop is near the base of the section. Beyond this outcrop chloritic sandstones and conglomerates begin to dominate the lithology showing a repeated stratigraphy, broad EW warping of S1, and minor kinking. Locally small rectangular pods, generally 2-3 mm long contain garnet replaced by chlorite.

Back up and continue down about 275 meters to path just before first fork in dirt road. Continue down beach a few meters.

A major NE-striking fault juxtaposes very deformed sandstone and conglomerate next to the schists. About 10 meters south an east-dipping scoop-shaped fault cuts into the outcrop. From here to the end of Beaverhead outcrop the structural style is basically the same with large ENE-trending presumably F2 folds clearly folding an intermediate, NW trending crenulation as well as S1. Faults separate similar fold interference patterns changing their orientations; however, the internal geometries of these fault blocks is consistant.

Return to top and continue down 100 meters to small cut-out off dirt road, a small path runs along edge and down to beach.

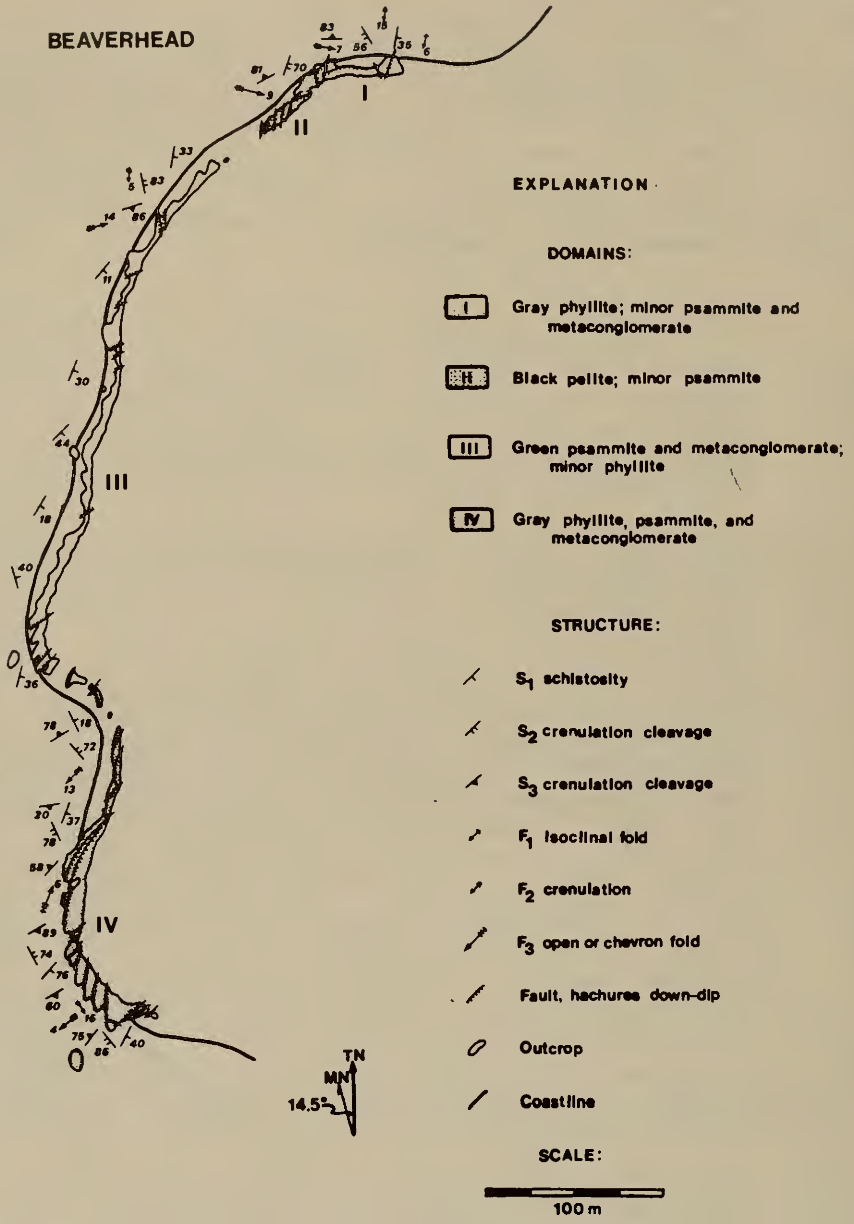

Figure 6. Geology of Beaverhead, Conanicut Island
R. Burks, 1981

The rocks visable on the coast to the southeast are pre-Pennsylvanian and are separated from these by the fault. Here the ENE trending F2 folds of the last outcrop swing into NE orientations which parallel the Beaverhead fault.

33.2 Return to Beavertail Road (1 mile) and retrace route north to Rte. 138.

35.0 Trace of the Beaverhead fault; Jamestown Historical Society Windmill (1787) on east side of North Main Road at. At the junction of Route 138 and North Main Road turn west (left) on Rte. 138 and approach east end of the Jamestown Bridge.

36.2 Park at the east end of the Jamestown Bridge, (near Jamestown Shores Motel), which connects Conanicut Island with the western shore of Narragansett Bay, and take the path down to the shore beneath the bridge.

STOP 5

Rhode Island Formation, Jamestown. Lithologies present include carbonaceous schist, conglomerate, and sandstone. The schist contains staurolite, garnet and biotite porphyroblasts in a matrix of biotite, muscovite, quartz, ilmenite, and dispersed organic matter. The porphyroblasts are post S1, but older than a well developed crenulation cleavage and associated retrograde metamorphism. The petrography is discussed in more detail in Grew and Day (1972) and Murray and others (this volume, Stop 6). S1 is approximately parallel to the bedding, at N20E; 30SE. Rare F1 isoclinal fold hinges are present. Younging based on cleavage/bedding relations indicate that the rocks are generally overturned. A NNE-striking crenulation cleavage (S2) and small amplitude F2 folds are sporatically developed. Pebbles are oblate in the plane of S1, and the long directions trend and Plunge to the NE. At the northern end of the outcrop, large amplitude (1 meter), recumbant folds trend N40E and are overturned to the north, deforming S1 and later quartz veins. Megafora of probable Westphalian D or younger age have been obtained from carbonaceous schist along the shore, 500m to the south (Quinn, 1963; Lyons in Skehan and Murray, 1980, p. 22).

38.2 Proceed west over the Jamestown Bridge, to the intersection of Routes 138 and 1A. Proceed west on Rte. 138 for 1.35 miles to Stook Hill roadcuts.

Stop 6

39.5 Rhode Island Formation, Stook Hill, Saunderstown. These outcrops represent an outstanding example of upper amphibolite facies rocks with well preserved primary structures. In order of decreasing abundance, the lithologies present are conglomerate, psammitic gneiss, carbonaceous schist, garnet amphibolite, and beryl-garnet pegmatite. The first four are considered to be metamorphosed Rhode Island Formation, while the pegmatite may be genetically related to the Narragansett Pier Granite. The predominantly overturned metasedimentary rocks contain a variety of relict textures (graded bedding, cross bedding, erosional contacts) indicative of a fluviatile origin.

The northern side of the roadcut consists is relatively coarse grained, and best displays primary structures, while the finer more abundant schists on the other sides contain the assemblage kyanite-staurolite-garnet-biotite-muscovite-quartz-ilmenite-graphite. Fine sillimanite needles along garnet/biotite contacts have also been reported (Grew and Day, 1972).

Along the northern side of the road, both bedding and cleavage (S1) strike E-W and dips gently to the north; NE-trending pebble elongation directions plunge 30NE. Tight minor folds are NE trending and have axial planes parallel to S1. Pebbles are oblate, and lie in the plane of S1. Both bedding and cleavage are more steeply dipping on the southern side of the road, and axes of boudins in the pegmatite trend E-W.

40.8 Return to the intersection of Routes 138 and 1A, and turn right (south) on 1A. Proceed south on Rte. 1A (Boston Neck Road) for 3.5 miles to turnoff (to the right) for Bonnet Shores. Bear right at the fork in the road, that comes very shortly, and proceed 0.9 mile. Turn right (as required) at one-way sign, and 0.2 miles later turn right at T-intersection. Three tenths of a mile later, park in small grassy field. The parking area as well as the shoreline exposures are on private property, and permission should be obtained.

45.7 Stop 7

Rhode Island Formation, Bonnet Shores. The shoreline exposures north of the beach consist of garnet zone metasediments cut by pegmatites presumed to be related to the Narragansett Pier Granite. The structure at this locality is more complex than that of the previous stops. More than three generations of folding and cleavage developement are easily observable, and multiple boudinage and faulting events have further complicated the structural geometry. The dominant fabric is a N15E 80SE S1 schistosity that is axial planar to tight NE trending folds which plunge shallowly to the NE. These early folds are well exposed in the sandy units on the west side of the point. The S1 surfaces are folded and cut by several later nearly coaxial structures, as well as EW crenulations (Fig. 7). On the eastern side of the point, the structure is dominated by NE and NW trending faults which usually show normal movement. In addition, both NS and EW extension has produced boudins, some of which may be pre- and syn- folding and/or faulting.

Retrace the route until back to Rte. 1A, and proceed south 2.3 miles. At a sign stating "Rhode Island National Guard, Camp Varnum Officer Candidate School", turn southeast on Old Boston Neck Road. If you have crossed the bridge over the Pettaquamscutt River, you have gone one bridge too far.

52.9 Take the secondary road 0.8 miles (or seven "roadhumps"), and park along road. The shoreline outcrops may be reached by walking approximately a quarter mile further along a private road. These outcrops are on private land and are not normally accessible and never without permission of the (obtained from the houses near the shore).

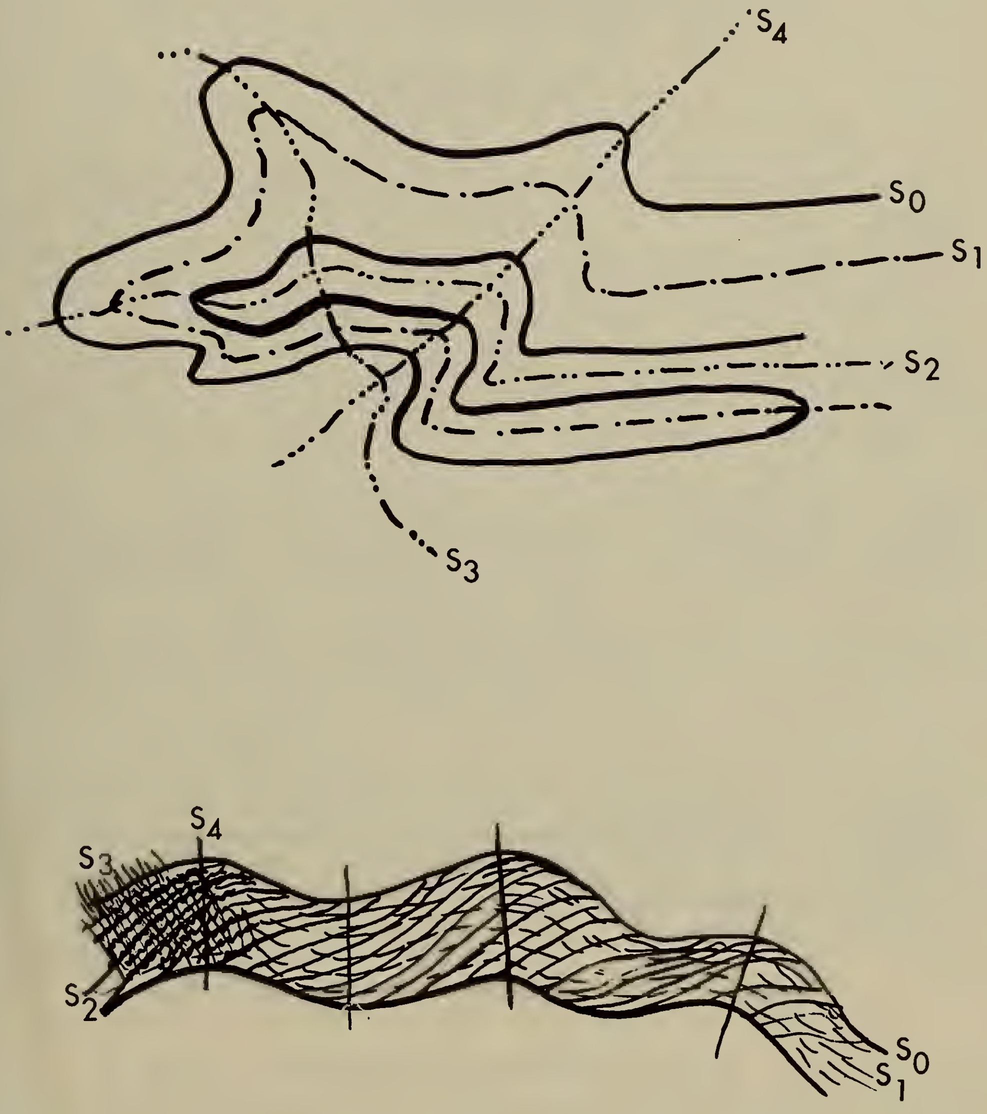

Fig. 7. Sketches of observable field relationships at Bonnet Shores. Four generations of cleavage formation and folding are shown.

53.7 Stop 8
Narragansett Pier Granite, Cormorant Point. The shoreline exposures consist of massive to gneissic garnetiferous granite and pegmatite, with roof pendants of Rhode Island Formation. A detailed map of this stop, as well as discussion of the granite's petrology, are given elsewhere in this volume (Hermes and others). The metasedimentary rocks consist of carbonaceous garnet-biotite schist, psammitic gneiss, and stretched pebble conglomerate. Although there are no chill zones, the granite clearly truncates the fabric of the schists. The well developed pebble elongation is NE plunging, while in most of the layers the schistosity is NE trending and SE dipping. The general consistancy of the orientation of individual layers with each other, as well as their concordance with the regional tectonic fabric of the southern part of the Narragansett Basin suggests that they are roof pendants. The dominant schistosity is considered S1, while a crenulation cleavage is interepreted as S2. Here, most (all?) of the deformation in the granite may be explained in terms of emplacement tectonics. However, to the north along the coast, the granite appears to have a more pervasive (regional?) fabric.

Granite petrology (see Hermes and others, this volume) and garnet/biotite equilibria in the roof pendants (Murray and Schwartz, unpub. data) suggests conditions of emplacement of $T=600+^{o}C$ and $P=5$ kbar. The change in granite color near the contact with the metasediments has been interpreted as the consequence of the interaction of contrasting fluid phases (from the granite and metasediments) along the contact (Murray and Skehan, 1979). An age of emplacement of 276 m.y. obtained from radiometric dates on monazites (Kocis and others, 1978), is consistant with the observation that the roof pendants contains Latest Pennsylvanian plant fossils (Brown and others, 1978). Incremental argon dates from biotites in the granite indicate closure temperatures were attained 235-250 m.y. (Dallmeyer, 1981).
Return to Rte. 1A, and proceed south or north, as you wish.

--- END OF TRIP ---

MAFIC DIKES OF NORTHEASTERN MASSACHUSETTS

Martin Ross
Northeastern University, Boston, MA 02115

INTRODUCTION

Over the past decade, interest in the mafic dikes of eastern North America has increased, beginning with the regional reconnaissance geochemical study of Mesozoic dolerite dikes by Weigand and Ragland (1970). McHone (1978), in a study of lamprophyre dikes of New England, also compiled the available chemical, field, and age data for northern New England Mesozoic mafic dikes in general. Only two dikes from northeastern Massachusetts are included in that compilation. Previous work in this area and eastern Massachusetts in general has been mainly field oriented with a limited amount of chemical and petrographic study (Shaler, 1889; Washington, 1899, Emerson, 1917; Wilson, 1901; LaForge, 1932; Bell, 1948; Skehan, 1975; Billings, 1976; Dennen, 1976; Koch, 1978; Ross, 1981). Emerson (1917) included a few chemical analysis including 3 of the Medford dike. Dennen (1951) reported partial major element chemical analyses of the Medford diabase dike and a diabase dike from Nahant as part of an investigation of chemical changes across igneous contacts. To date, a detailed, systematic field and petrologic investigation of the mafic dikes in this area has not been conducted. The present study was begun in 1979 (some sampling was done in 1970-72) as an initial step toward producing detailed field, petrographic and geochemical information for the mafic dikes in the area.

From Boston north to Cape Ann, hundreds of mafic dikes intrude rocks that range in age from Precambrian to Carboniferous (?). Most of the dikes are generally regarded as Mesozoic but some may be as old as Precambrian. Four whole rock K-Ar ages of diabase dikes in the area range from 254 to 334±15m.y. (Zartman and others, 1970). Only 2 dikes dated since 1970 yield Mesozoic K-Ar ages and most minimum ages fall between 300 and 350 m.y. (H.W. Krueger, unpublished data).

MAFIC DIKE PETROGRAPHIC TYPES

At least 5 major petrographic varieties and 6 subvarieties have been recognized among the 46 dikes studied so far. Three of the main varieties are at present, represented by a single dike each. The majority of the dikes can be categorized as diabases (i.e. altered dolerites) and dolerites with the distinction based on the degree of sausuritization of plagioclase, uralitization of clinopyroxene (primarily augite), alteration of olivine, and relative abundances of other secondary phases (mainly chlorite, epidote, and carbonate). The degree of alteration in the dolerites ranges from nearly none to moderate in which uralitized margins account for less than about 50 percent of the volume of individual pyroxene grains, and twinning is still clearly visible in sausuritized plagioclase grains. In the diabases, the degree of alteration ranges from the maximum described above for dolerites to virtually total alteration of the essential minerals. Chlorite (often pennine) and epidote are far more abundant in the diabases (Table 1).

Diabases

The 22 diabase dikes studied can be further broken down into four petrographic subvarities: 1) 10 aphyric, 2) 3 aphyric with altered olivine 3) 5 plagioclase phyric ± minor-biotite, and 4) 2 plagioclase-phyric with altered olvine. Three aphyric diabases at Pine Hill contain brown amphibole (uralite). Representative modal analyses are shown in Table 1. Aphyric samples and groundmasses of phyric diabases tend to be fine- to medium-grained, equigranular and typically intergranular. Ophitic and subophitic textures are well-developed toward the centers of thicker dikes. Microporphyritic texture is typical of chilled dike margins and also in groundmasses of some phyric dikes. Glommeroporphyritic clusters of plagioclase phenocrysts and microphenocrysts are also fairly common (most plagioclase = andesine-labradorite).

Dolerites

The 19 dolerite dikes can be grouped into the following petrographic subvarities: 1) 9 are aphyric, 2) 4 areplagioclase-phyric, and 3) 5 aphyric and 1 plaioclase-phyric dike contains what appears to be subhedral to euhedral olivine altered to chlorite and magnetite ± calcite. Textures are as described above for the diabases with ophitic and subophitic textures generally better developed and more common. Plagioglcase phenocrysts tend to be smaller and less abundant. Representative modal analyses are shown in Table 2. Most of the plagioclase is andesine to labradorite.

Megacryst-rich Diabase

Plagioclase megacryst-rich diabase dike from Rockport has been examined and constitutes a petrographic type of its own. The plagioclase megacrysts increase in size and abundance toward the center of the dike where they attain a maximum length of at least 9.2 cm and account for approximately 35 volume percent of the rock (megascopically). Plagioclase phenocrysts and megacrysts make up as much as 53 percent of the mode (Table 1). The anorthite content of the phenocryst cores decrease from about An49 at the dike margin to An40 near its center. This dike contains more biotite than any other dike examined (Table 1).

Lamprophyres

Hyalo-monchiquite

A lamprophyre dike (hyalo-monchiquite) has been examined from Pine Hill and its modal analysis is shown in Table 1. Microphenocrysts of kaersutite and what appears to be a ferromagnesian mineral (olivine or pyroxene) completely altered to chlorite and magnetite (the latter along relic fractures) are set in a groundmass of clear to brownish glass and small microlites. The microlites consists of kaersutite, fresh augite and an opaque accessory mineral (probably magnetite). Both the Kaersutite and augite microlites are elongate prismatic grains. Small ocelli of analcime, kaersutite, and opaques are present as are irregular-shaped amygdales filled with calcite and zeolite.

Camptonite

An unusual camptonite dike containing abundant megacrysts, xenocrysts, and xenoliths was recently exposed in the subway tunnel being excavated beneath Porter Square in Cambridge. The dike was mapped by J. Chamness and R. Dill of Haley and Aldrich, Inc. and a large number of samples collected by J. Chamness have been provided to supplement the four samples collected by the author. The dike trends N15° to 20°E, is vertical, and has a maximum thickness of about 2.4 meters. Handspecimens will be brought on trip.

The plagioclase (An40) of the host lamprophyre occurs as late-forming, anhedral, lath-shaped grains riddled with euhedral poikilitic inclusions of augite, altered olivine, kaersutite, biotite, apatite, and opaques. These minerals also fill interstices between plagioclase laths giving the rock an intergranular texture. The plagioclase is fresh in contrast to the feldspar xenocrysts which are more sericitized.

The dike margin is aphanitic and free of xenoliths and xenocrysts within about 2.5 centimeters of the contact. Microcline and oligoclase xenocrysts begin to appear and become larger and more abundant between 5 and 9 cm of the dike margin where phenocrysts of biotite and amphibole (kaersutite ?) and small xenoliths also first start to occur. Locally between about 9 and 20 cm of the dike margin, feldspar xenocrysts up to about 4 cm long show marked flow alignment parallel to the dike contact. The xenoliths, xenocrysts, and megacrysts all increase markedly in size and abundance and the groundmass coarsens to become fine-grained at the center of the dike. Euhedral Kaersutite megacrysts of at least 8.0 cm length, biotites up to at least 5.5 cm in diameter, and plagioclase xenocrysts up to at least 7.5 cm in length are common within the central portion of the dike. Many of the feldspars are shattered and, when viewed in thin section, both microcline and oligoclase are embayed and corroded by the groundmass which strongly suggests they are xenocrysts and not megacrysts.

The xenoliths are angular up to at least 16 cm in diameter, and lack any megascopically visible reaction features at their margins. Rock types represented include pink medium- to coar-grained granitoid, (some resemble Dedham Granodorite) pink, medium-grained, garnetiferous quartzo-feldpathic gneiss, Cambridge Argillite, felsite (Lynn Volcanics ?), gray, garnetiferous, augite-bearing granulite, and what appears to be an ultramafic rock. Except for the Cambridge Argillite, possible Dedham Granodiorite, and the felsite, none of the xenoliths examined megascopically resemble rocks exposed at the surface in the greater Boston area, and some appear to be of deep crustal and, perhaps, mantle origin.

Similar dikes in southwestern Rhode Island have been described in detail (Leavy and Hermes, 1977) and it is not inconceivable that the Porter Square dike is related to that series although the host rocks are chemically quite dissimilar. LaForge (1932) briefly described 2 "inclusion-bearing dikes" trending between due north and N25°E that cut Cambridge "slate" in the old Mystic Quarry in Somerville. Inclusions of Dedham Granodiorite and Lynn Volcanics and pieces of minerals and rocks not found at the surface in the Boston area are present (LaForge, 1932). This dike has not yet been observed by the author but could easily be a northeast extension of the dike beneath Porter Square.

Medford Dolerite Dike

The Medford dike attains a thickness of 122 meters at Pine Hill, Medford and is petrographically distinct from the other dike groups (Table 1). It has traditionally been considered a diabase (Wilson, 1901; LaForge, 1932) but Skehan (1975) refers to it as a diorite. Based on its plagioclase anorthite content (An70 cores, An29 rims) an SiO_2 content less than 52% (Table 2), ophitic to subophitic texture, and relatively unaltered mineralogy, it is a biotite-rich dolerite containing minor quartz and granophyre (using the nomenclature of this report). A modal analysis of one sample from the interior of the dike at Pine Hill is listed in Table 1 and a chemical analysis in Table 2.

Dike Chemistry

Nine new major and partial trace element analyses of 7 selected dikes suggests a broad range of compositions are represented (Table 2). The mean of 3 Medford dike analysis (Emerson, 1917) are also listed for comparison. Alkali-silica plots using the alkaline-tholeiite discriminant of Irvine and Baragar (1971) indicates 6 dikes are alkaline and 2 are tholeiitic. The alkaline dikes can tentatively be subdivided into 4 chemical types: 1) two plagioclase-phyric diabases have relatively low SiO_2 and CaO and high Al_2O_3 and TiO_2 (samples 107 & 127Table 2), 2) one aphyric doloerite has relatively high SiO_2, CaO, TiO_2, and P_2O_5, and low Al_2O_3 (sample 51 Table 2), 3) the groundmass of the xenolith and xenocryst-rich camptonite has low SiO_2 and TiO_2, very low CaO, and high Al_2O_3, Zr, Sr, and Rb (sample 19 Table 2), and 4) the plagioclase megacryst-rich diabase is highest in SiO_2, Al_2O_3, and total alkalis (1 and 9, Table 2). The Medford dike may be a fifth alkaline type having the lowest TiO_2 and highest Al_2O_3 (Table 2) but new analyses are in progress.

The two tholeiitic dolerites form two chemical types on the basis of high and low TiO_2 contents (nos. 112 and 13, Table 2). The possible effects of alteration on dike chemistry could account for some of the variation detected. Decreases in CaO, MgO, and SiO_2, and increases in Fe^{3+}, Na_2O, K_2O, and H_2O have been documented for Mesozoic basalts of the Newark and Hartford Basins and attributed to possible interaction of basalt with sea-water at low temperatures (Puffer and others, 1981).

Dike Ages

Whole-rock K-Ar ages have been published (Zartman and others, 1970) for four "basalt dikes" between Boston and Rockport which have not yet been sampled as part of this study. Their ages range between 254 and 334 ± 15 m.y. Four of the dikes included in the present study have also been dated (K-Ar whole-rock) by H.W. Krueger of Geochron Laboratories, Inc. and are as follows: 383 ± 23 m.y. and 299 ± 21 m.y. for two olivine-bearing dolerites at Stop 2, Saugus ; 202 ± 8 m.y. for the camptonite at Porter Square, Cambridge, and 190 ± m.y. for the Medford dike at Pine Hill, Medford (Stop 1) (H.W. Krueger, personal communication, 1981).

LaForge (1932) grouped the mafic dikes in the Boston area into four sets on the basis of their trends and cross-cutting relationships: 1) an older east-west set found only in pre-Carboniferous rocks south of Boston and are scarce; 2) a younger (late Carboniferous) east-west set (N. 60° W to S. 75°W) which cut all formations in the area, are up to 152 m thick, commonly porphyritic and includes sills up to 9 m thick; 3) a northwest-southeast set which is locally cut by the younger east-west set but elsewhere occur as offshoots from it; 4) a north-south set (due to north to N25°E) of olivine diabases (Triassic) cutting all other units and with a maximum thickness of 12 meters. LaForge (1932) treated the Medford dike as a Triassic unit by itself.

All but three of the dikes studied so far can be placed in sets 2 through 4 above. Five aphyric diabases, 6 aphyric dolerites, and 3 plagioclase-phyric dolerites have strikes within the range of LaForge's younger east-west set. Seven aphyric diabases, 5 plagioclase-phyric diabases, 1 plagioclase-phyric dolerite and the plagioclase megacryst-rich diabase have northwest-southeast trends. Three aphyric diabases, 1 plagioclase-phyric diabase, 2 aphyric dolerites, 2 lamprophyres, and the Medford diabase dike fall within the range of LaForge's (1932) north-south set. A third lamprophyre recently sampled with G. McHone at Chubb Point at the south end of Manchester (originally mapped by Shaler, 1899) trends N15°E and 2 north-south trending dikes mapped as lamprophyres by Wilson (1901) are present at Pine Hill, Medford but have not yet been verified by thin section analysis. Three aphyric dolerites have northeast-southwest trends and cannot be grouped into any of LaForge's sets.

Of the chemically analyzed dikes, the two tholeiitic, aphyric dolerites have northeast trends; one Siluro-Devonian, alkaline, aphyric dolerite trends N65°W; the camptonite trends about N15°E (J. Chamness, personal communication); the alkaline Medford dolerite dike has an average trend of N 19°E (LaForge, 1932); and the alkaline, plagioclase megacryst-rich diabase dike at Rockport trends N 14°W.

At the south end of Marblehead neck (Stop 5) a northeast trending aphyric, tholeiitic dolerite and 2 aphyric diabases (NE and due north trends) are cut by an alkaline, plagioclase-phyric, northwest trending diabase which in turn is cut by another thinner alkaline, plagioclase-phyric, northwest trending diabase (Ross, 1981). At this locality then, the northwest trending porphyritic diabases are the youngest units. It is clear from evidence at this locality that assuming altered dikes (diabases) to be older in general than unaltered dikes (dolerites) is not valid.

A tentative listing by relative ages from oldest to youngest for dikes in the area of the present study would be as follows: aphyric, northeast to east-trending diabases; aphyric, northeast-trending, tholeiitic dolerite; two sets of plagioclase-phyric, northwest trending, alkaline diabases; aphyric, east-west to northwest trending, tholeiitic dolerite; the alkaline, Medford dolerite; and north to northeast trending lamprophyres. More petrographic, chemical, and field data are required in addition to age dating before a more definite scheme of relative and absolute ages can be established.

TABLE 1. Representative modal analyses of mafic dikes, northeastern Massachusetts[1]

Sample Number[2]	51	112	13	127	107	111	MED	9	20	221
Total Plagioclase	61.6	55.3	49.5	44.1	58.5	61.3	67.5	75.7	61.1	-
Phenocrysts	2.7	-	1.7	4.5	trace	-	-	53.1	-	-
Total Augite	24.7	37.0	39.4	39.9	21.0	25.7	18.2	12.8	20.2	4.2
Uralitized	3.8	26.0	4.3	36.0	17.0	22.2	1.8	11.1	13.1	-
Opaque Accessories	8.7	5.8	7.1	4.5	8.9	7.9	2.5	3.1	12.0	13.4
Nonopaque Access.[3]	2.5	0.9	1.0	-	1.3	0.1	1.9	0.6	1.1	-
Altered Olivine	-	trace	trace	-	-	trace	-	-	1.4	2.4
Biotite	-	-	0.2	-	-	-	6.1	7.3	4.0	-
Kaersutite	-	-	-	-	-	-	-	-	-	32.0
Ocelli	-	-	-	-	-	-	-	-	-	7.4
Glass/mesostasis	-	-	-	-	-	-	-	-	-	40.6
Other Secondary	2.5	1.0	1.0	2.3	10.3	5.0	1.8	0.5	0.1	-
Chlorite	2.5	-	1.0	2.3	10.3	2.1	0.8	0.5	0.1	-
Epidote	-	1.0	-	0.3	-	2.9	0.5	-	-	-
Carbonate	trace	-	-	-	trace	-	0.5	-	-	trace

[1] Modal analyses based on 1000 points counted per thin section.

[2] See Table 2 for sample localities except the following: 111, aphyric diabase, Marblehead Neck (Dike C, Fig. 4); 221, hyalo-monchiquite, Pine Hill, Medford (dike 8, Fig. 2); 20 is coarser sample from interior of same dike as sample 19, Table 2.

[3] Typical accessories are apatite ± quartz

TABLE 2. Chemical analyses of mafic dikes, northeastern Massachusetts[1]

Samples[2]	107	127	112	13	51	1	9	19	MED
SiO_2	44.7	45.1	48.1	47.5	47.2	49.1	49.0	46.5	46.82
Al_2O_3	16.2	16.1	14.9	13.5	14.3	14.6	17.9	16.0	20.46
CaO	8.54	9.38	11.1	10.6	9.41	6.90	7.73	4.46	7.40
MgO	4.96	6.03	5.23	2.54	4.26	2.53	2.54	4.28	3.13
Na_2O	3.35	2.32	2.58	2.81	2.71	4.28	4.35	3.94	3.17
K_2O	1.09	1.80	0.60	0.65	1.56	2.69	1.97	2.21	2.10
FeO	14.0	11.6	11.5	12.9	12.6	11.7	10.6	12.2	13.09
MnO	0.21	0.18	0.20	0.22	0.24	0.26	0.23	0.14	0.73
TiO_2	3.09	3.03	2.07	3.03	3.14	2.42	2.27	1.99	0.33
P_2O_5	0.62	0.38	0.40	0.44	1.31	1.28	1.31	1.02	0.69
L.O.I.	2.39	2.47	1.62	1.77	2.47	1.08	1.00	4.85	2.35
Trace elements (ppm)									
Cr	30	170	140	230	50	40	20	80	
Zr	200	160	190	170	230	340	290	460	
Sr	630	620	600	360	580	620	840	1100	
Rb	30	40	10	80	20	50	10	100	

[1] XRF analyses by X-ray Assay Laboratories Ltd.

[2] Sample locations and dike types:

107: dike B, Marblehead Neck; plagioclase-phyric diabase; alkaline.
127: dike I, Marblehead Neck; plagioclase-phyric diabase; alkaline.
112: dike D, Marblehead Neck: aphyric dolerite; tholeiitic.
13: dike along Rte. 93 near Pine Hill, Medford; mean of two analyses; aphyric dolerite; tholeiitic.
51: dike 7 behind K-Mart, Saugus: aphyric dolerite; alkaline.
1: Rockport Headlands; plagioclase megacryst-rich diabase, contact.
9: Center of dike 1 above; alkaline.
19: Porter Square, Cambridge subway tunnel; xenolith-rich camptonite.
MED: Medford dike at Pine Hill, Medford (Emerson, 1917); mean of three.

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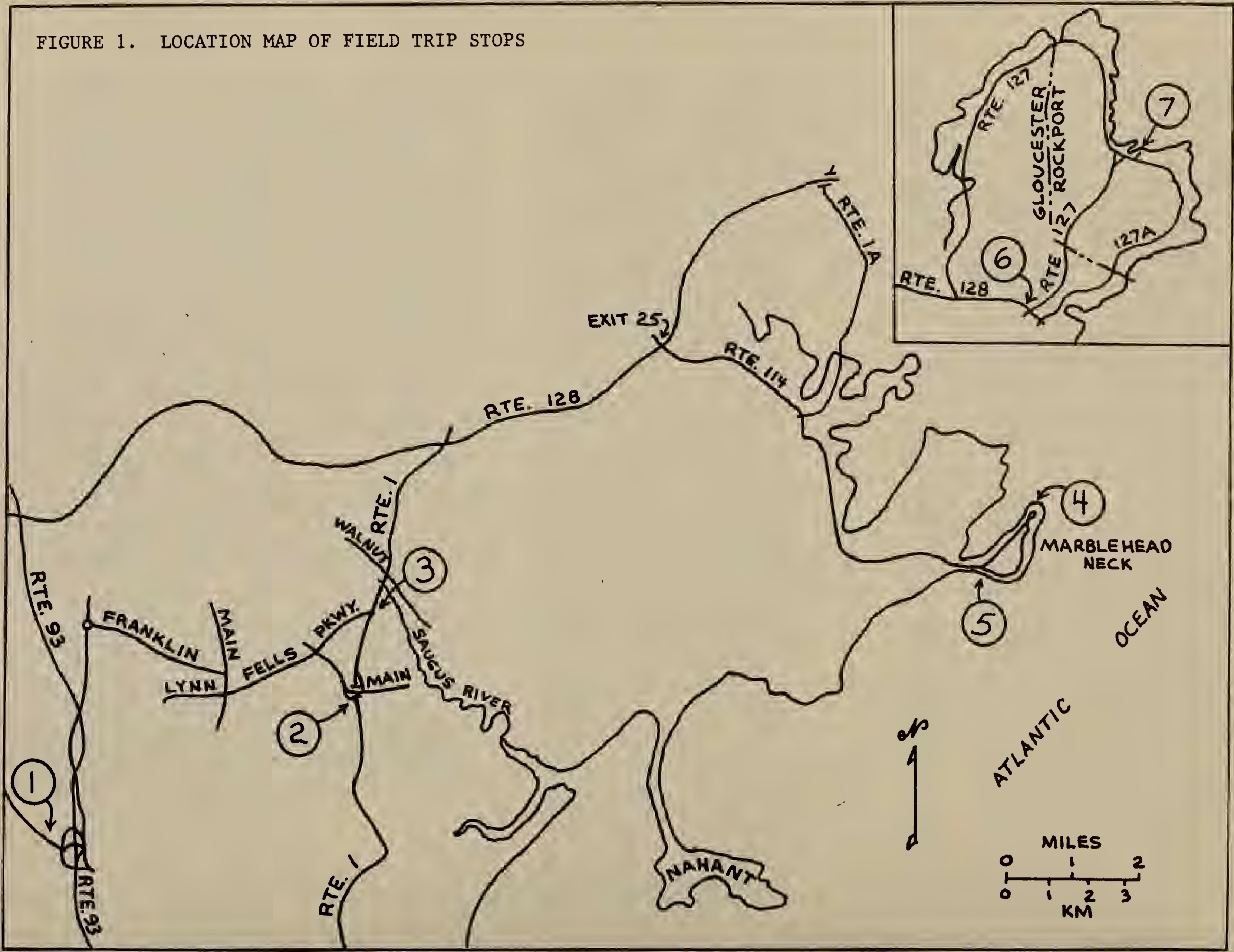
ITINERARY

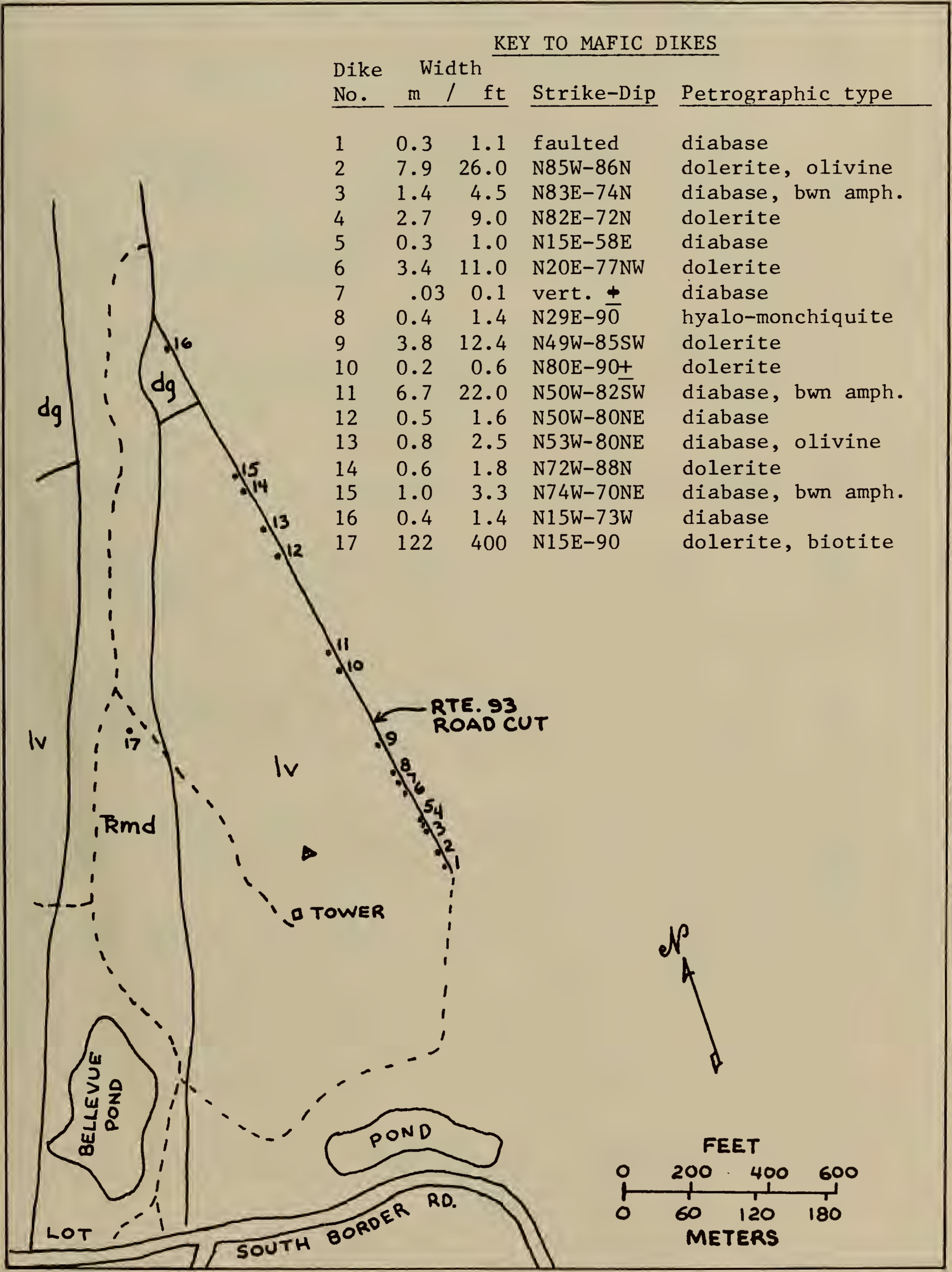
Assemble in the Keeney parking lot on the University of Rhode Island campus for departure at 7:30 A.M., Sunday, October 18. Stop 1 will be at Pine Hill in the Middlesex Fels Reservation, Medford, Massachusetts. This locality can be reached in approximately 3 hours by travelling north from Kingston, R.I. and through Providence via Interstate 95 to its junction with Rte. 128 approximately 25 miles north of Providence. Proceed east on Rte. 128 (and Interstate 93) into and through Boston via Rte. 93 to its junction with Rte. 28, Medford, Mass. Take Rte. 28 Fellsway West exit and continue on elevated traffic circle back over Rte. 93 and take first right off circle onto South Border Road. Proceed 0.3 miles and enter gravel parking lot on right at Bellevue Pond at the base of Pine Hill, Medford, Massachusetts. This is Stop 1 (see Figure 1).

Mileage

0.0 STOP 1. MEDFORD AND OTHER MAFIC DIKES AT PINE HILL: Walk north 300 feet along trail on east side of Bellevue Pond to old dirt road branching off to the right (east). Bellevue Pond and the parking lot are located within the interior of the Medford dolerite dike (Figure 2). Follow the road to right for approximately 425 meters (1400 feet) keeping to the right of the cyclone fencing. Follow the fence north to the road cut along Interstate 93. At least 16 mafic dikes cut the Lynn Volcanics and Dedham Granodiorite along approximately 580 meters (1900 feet) of road cuts. See Skehan (1975) for a description of the general geology of the Pine Hill area, and Zarrow (1978) for a detailed account of the stratigraphy of the Lynn Volcanics and their relationship with the Dedham Granodiorite. The locations, attitudes, thicknesses, and dike types are shown on Figure 2. Dike 8 (Figure 2) is noteworthy in that it is a hyalo-monchiquite. This dike is described earlier in this report and its mode is shown on Table 1 (as is the Medford dike). The hyalo-monchiquite is darker in outcrop than is typical of the lamprophyres in the rest of New England (J.G. McHone, personal communication).

FIGURE 1. LOCATION MAP OF FIELD TRIP STOPS





KEY TO MAFIC DIKES

Dike No.	Width m	/ ft	Strike-Dip	Petrographic type
1	0.3	1.1	faulted	diabase
2	7.9	26.0	N85W-86N	dolerite, olivine
3	1.4	4.5	N83E-74N	diabase, bwn amph.
4	2.7	9.0	N82E-72N	dolerite
5	0.3	1.0	N15E-58E	diabase
6	3.4	11.0	N20E-77NW	dolerite
7	.03	0.1	vert. ±	diabase
8	0.4	1.4	N29E-90	hyalo-monchiquite
9	3.8	12.4	N49W-85SW	dolerite
10	0.2	0.6	N80E-90±	dolerite
11	6.7	22.0	N50W-82SW	diabase, bwn amph.
12	0.5	1.6	N50W-80NE	diabase
13	0.8	2.5	N53W-80NE	diabase, olivine
14	0.6	1.8	N72W-88N	dolerite
15	1.0	3.3	N74W-70NE	diabase, bwn amph.
16	0.4	1.4	N15W-73W	diabase
17	122	400	N15E-90	dolerite, biotite

FIGURE 2. Geologic sketch map of Pine Hill, Medford. Dedham Granodiorite (dg), Lynn Volcanics (lv), and Medford dike (TRmd) mapping after Wilson (1901). Road cut data by author.

The contact between the Lynn Volcanics and Dedham Granodiorite is exposed in the road cut between dikes 15 and 16 and is interpreted as an intrusive contact by Zarrow (1978). Note the thin diabase dike (16 on Fig. 2) nearly parallel to the roadcut. The Medford dike is exposed just beyond this dike.

Walk away from the highway at the flat area beyond the exposure of Medford and cross the downed portion of the cyclone fence and follow trail uphill into the reserve. This trail follows the axis of the Medford back to the parking lot. Note the numerous old quarry pits in the Medford dolerite. Side trips up onto Pine Hill and the tower to observe cross cutting dikes and the Boston Basin will be made if time permits.

0.3 Return via South Border Road into traffic circle and take exit northbound onto Rte 28 Fellsway West and proceed north on 28 parallel to Rte 93 to Stoneham.

3.9 Right (east) on Franklin St. in Stoneham.

6.0 Turn right (south) on Main St., Melrose and south to Lynn Fels Parkway.

6.2 Turn left (east) at Lynn Fels Parkway (easy to miss, Lynn Fels Pkwy has median divider). Proceed northeast 1.6 miles.

7.8 Turn right onto Main St., Saugus.

8.5 Take sharp right turn into K-Mart parking lot just short of overpass. Drive around right side of K-Mart and park behind store at curb on right along old quarry face. Stop 2 begins at north end of exposure.

STOP 2. DIKES CUTTING DEDHAM GRANODIORITE BEHIND K-MART: At least 13 dolerite and diabase dikes intrude Dedham Granodiorite at this locality. See Fig. 3 for locations, attitudes, and dike types. The dominant dike trend is northwest-southeast with a few dikes trending nearly east-west. The Dedham Granodiorite and dikes 6 and 7 have K-Ar ages of 600 m.y., 299 ± 21 m.y. and 383 ± 23 m.y. respectively (H. Krueger, personal communication, 1981). The chemistry of dike 7 is shown in Table 2 and its mode in Table 1. Dike 3 is offset by a SE-dipping fault containing slickensides trending N55-60°E. A thin , aphyric diabase dike is cut by the thicker aphyric dolerite and at the south end of the quarry (dikes 10 and 11 respectively, Figure 3).

Return to cars and leave parking lot via exit a north end. Take overpass over Rte 1 and turn left into northbound entrance to Rte 1 and proceed north on Rte 1.

9.9 Continue 0.1 miles beyond Lynn Fells Parkway overpass and park in large parking lot of Caruso's Diplomat restaurant just beyond gas station on right. Lock cars and walk back few hundred feet along Rte 1 and follow along highway side of river to spectacular

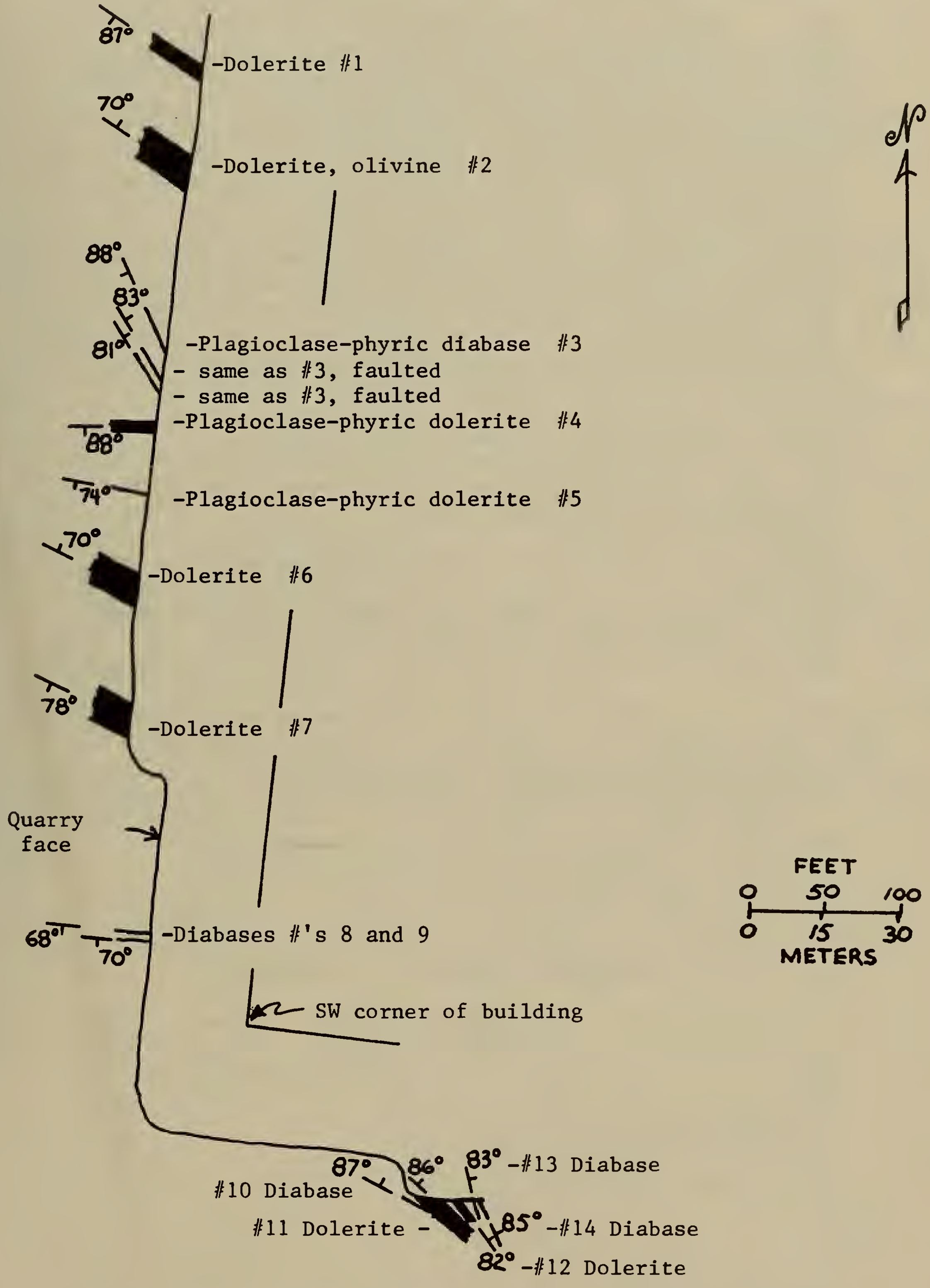


FIGURE 3. Geologic sketch map of mafic dikes intruded into Dedham Granodiorite behind K-Mart, Route 1, Saugus (STOP 2).

exposures on opposite side of the Saugus River.

STOP 3. DIKES CUTTING DEDHAM GRANODIORITE AT SAUGUS RIVER: The northernmost thick dike (strike N83°W, 85°S dip) is an aphyric dolerite cutting Dedham Granodiorite and a large foliated xenolith contained within the Dedham. This and the other dikes are also exposed in the excavation on the highway side of the river. The branching, aphyric dolerite dike (strike N57°E, dip 74°NW) appears to be a single dike lacking interior chilled margins where the two branches merge. Note the thin vertical offshoot across the river extending along a joint above the sharp corner of the dike branch. The Dedham appears slightly more mafic adjacent the north side of the exposure of the branching dike on the highway side of the river. This may represent a subtle contact metamorphic aureole related to the dike. Two thin plagioclase-phyric dolerite dikes occur south of the branching dike. The southernmost of these is exposed on our side of the river also.

Return to the cars and continue north on Rte 1.

12.9 Exit right at junction of Rtes 1 and 128 and follow signs for Gloucester and north via Rte 128.

16.4 Take Rte 114 at Exit 25 for Salem and Marblehead.

17.0 Left at light, go one block, turn right (still on Rte 114).

17.6 Right (SW) at intersection with Rte 35, still on Rte 114 (North St.).

18.9 Cross Rte 107 at intersection and continue on Rte 114, Marblehead.

19.2 Enter long traffic circle and pass Salem train station and take exit to Derby St. Continue to LaFayette St. and turn Right (south).

20.6 Bear left at light and continue on Rte 114 past Salem State College and cross end of Salem Harbor and enter Marblehead.

21.6 Left at intersection past cemetery, stay on LaFayette St.

22.2 Continue straight through light onto Pleasant St.

22.6 Right on Ocean Ave., continue until across causeway at harbor.

23.5 Bear right on Ocean Ave. and continue around Marblehead Neck.

23.9 Ocean Ave makes sharp left then right.

24.8 Right on Ocean Ave to Follett St.

25.0 Left on Follett Street to Chandler-Hovey Park. Park in lot or along Follett St. Stop 4.

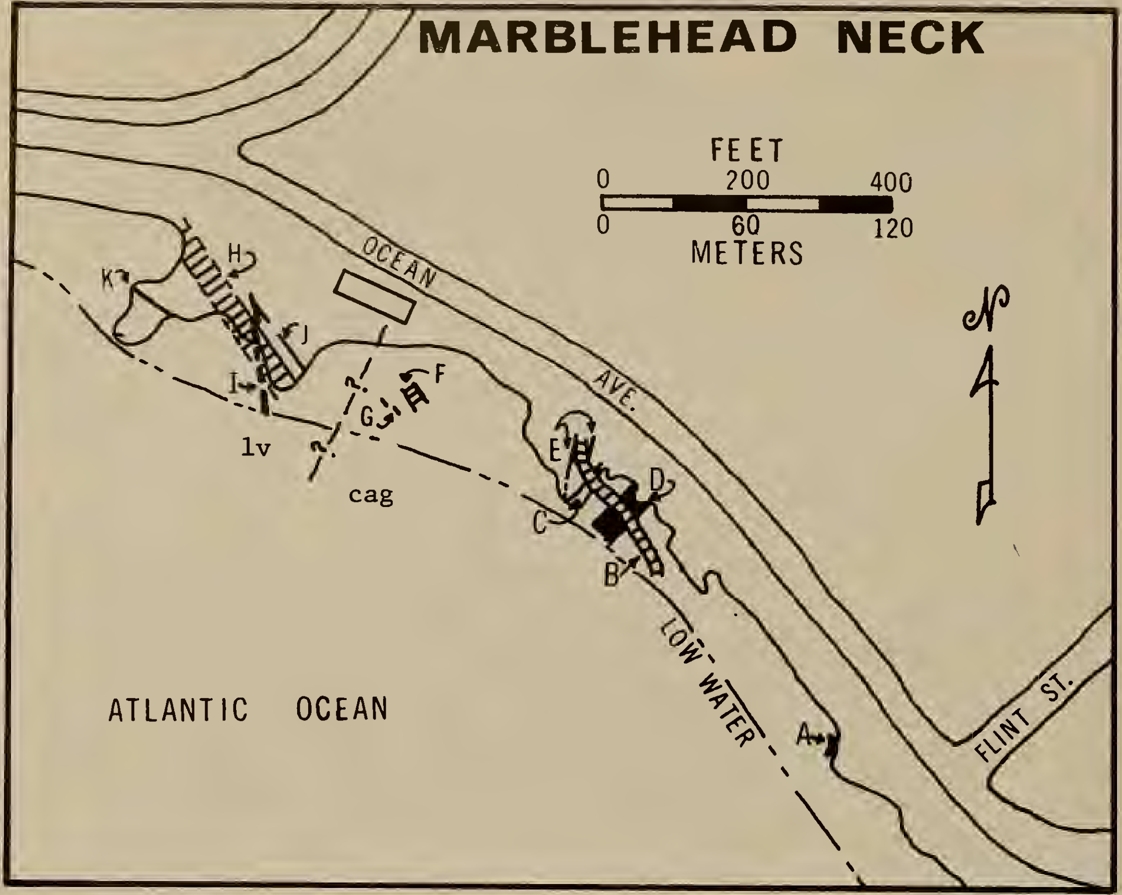
25.1 STOP 4. CHANDLER HOVEY PARK: A plagioclase-phyric diabase and an aphyric dolerite cut Lynn Volcanics exposed along the shore just north of the parking lot. The 4.8 m thick diabase strikes N 15° W and dips 70°W and the 1 thick dolerite strikes N 4° E and dips 55° E. These trends are essentially parallel to a joint set in the Lynn.

Accelerated erosion along the dike contacts and the northerly-trending joints in the Lynn has created a series of north-trending re-entrants retreating into the park. Mafic dikes exposed along the Massachusetts shoreline are typically quarried out by wave action at a faster rate than the country rock, especially if the latter is massive rock. Dike contacts are points of weakness that typically erode more rapidly than dike interiors. Cooling joints within mafic dikes form perpendicular to the dike contact (the cooling surface) to form crude to well-developed columns. These smaller diameter columns may terminate at a cooling joint which is a short distance into a dike and oriented parallel to the contact. A second, usually larger diameter and cruder set of joints may continue into a dike and terminate at a second joint parallel to the dike trend. The mirror image of this jointing extends from the dike center out to the opposite contact. This pattern of columnar jointing is best developed in thinner dikes and dikes in which chilling against colder wallrock was more pronounced.

The degree of development of cooling joints in a mafic dike and pre-existing joints in the country rock as well as the joint and dike trends relative the shoreline are far more important controls of the relative rate of erosion of dike and country rock than possible differences in the degree of chemical weathering.

Retrace our route to Ocean Avenue and back to south end of Marblehead Neck (beach visible along south side of road). Proceed to intersection just short of the causeway and park along the right side of Ocean Avenue (don't block driveways). Walk across Ocean Avenue to small park (with bench) near causeway.

26.7 STOP 5. DIKES AT SOUTH END OF MARBLEHEAD NECK: A series of at least 10 dikes and offshoots are well-exposed along the east-west trending shoreline (Figure 4). Dikes H, F, and B (Fig. 4) are identical in hand-specimen and thin section and probably represent en echelon segments of a single plagioclase-phyric diabase dike. Lack of exposures does not permit observing if the segments are offset by faulting or merely intruded along en enchelon joints as is characteristic of dikes of the Columbia River Basalt Group of Oregon and Washington. Dike J is probably a small offshoot of the larger dike (Fig. 4). Both J and segment H are cut here by 0.9 m thick plagioclase-phyric diabase dike trending N 9° E to N 20° W and dipping W to SW 40° to 65°. The southwest half of dike segment H and a thin aphyric dike farther



KEY TO MAFIC DIKES

Dike	Width m	Width ft	Dip	Petrographic type	Chemical type
A	2.5	8.1	80W-90	plagioclase-phyric diabase	=B?
B	6.0	19.8	86NE	plagioclase-phyric diabase	alkaline
C	1.2	3.9	68NW	diabase	
D	10.4	34.0	66NW	dolerite, olivine	tholeiite
E	0.7	2.2	81W±5	diabase	
F	7.3	24±1	84SW	plagioclase-phyric diabase	=B
G	0.6	2.0	65SW	diabase, rare plag. phenocrysts	
H	9.1	30.0	80NW	plagioclase-phyric diabase	=B
I	0.9	3.0	40W	plagioclase-phyric diabase	alkaline
J	1.8	1-6.0	vert.	plagioclase-phyric diabase	=B
K	0.3	1.0	vert.	diabase? no thin section	

FIGURE 4. Geologic map of mafic dikes intruded into Cape ann Granite (cag) and Lynn Volcanics (lv) at south end of Marblehead Neck (Stop 5).

out on the point (deep notch) have been deeply eroded. Chemical analyses of dikes B (H and F), D, and I are listed in Table 2 and modal analyses are shown in Table 1.

The dikes within the park have intruded Lynn Volcanics but exposures to the east along the beach are in what appears to be Cape Ann Granite according to Skehan (1975). The contact between Lynn and Cape Ann is covered by the beach and riprap but must lie approximately where shown on Figure 4. At low tide the exposures to the east can be reached by the beach and, at high tide, via the sidewalk along Ocean Avenue.

Dike B (= H and F) cuts two aphyric dolerite dikes (D and E, Fig. 4) and a thin, aphyric diabase dike (C). Xenoliths of granite are present within the dike. A large, foliated biotite granulite (Skehan, 1975) can be seen within the Cape Ann Granite at locality F and is cut by dikes B and D as well. Dike D is tholeiitic in contrast to dikes B and I which are alkaline (Table 2). Approximately 120 m farther east from dike B a plagioclase-phyric diabase dike is present and is somewhat less altered than either dikes B or I. Definite correlation with either will require a chemical analysis but it is tentatively considered equivalent to B.

It is clear from cross cutting relationships, petrography, and chemical compositions that at least 4 episodes of mafic dike intrusion are represented here. Two sets of alkaline, north to northwest-trending plagioclase-phyric diabase dikes post-date a tholeiitic, northeast-trending, aphyric dolerite dike and two NE-trending, aphyric diabase dikes.

Retrace our same route all the way back through Salem to Rte. 128.

33.8 Turn north on Rte. 128 at Exit 25 toward Gloucester and Rockport.

38.5 100 feet north beyond the exit from the Howard Johnson service area a northeast-trending mafic dike exhibiting well-developed columnar jointing perpendicular to contacts is exposed on right.

57.2 Park right in breakdown lane at bottom of long hill just before Exit 10 in Gloucester. Walk across Rte 128 to large roadcut.

STOP 6. DIKE AND XENOLITHS IN CAPE ANN GRANITE: The xenoliths are gabbro porphyry with labradorite phenocrysts (Dennen, 1976), suggesting the presence of a mafic pluton somehwere at depth beneath Cape Ann.

Note a 42 cm thick, plagioclase-phyric dolerite dike trending N 30° E and dipping 60° NW.

Turn left at Exit 10 onto Rte. 127 and drive north to Rockport.

59.9 Continue straight at "Five Corners" intersection onto Broadway.

60.3 Turn right at Rte 127A (South Street), two blocks and LEFT on Norwood Avenue for three blocks then left on Highland Ave. and park on right. Walk down hill on Highland Ave. to asphalt path to right. Follow path out to Rockport Headlands and Stop 7.

STOP 7. PLAGIOCLASE MEGACRYST-RICH DIKE AT ROCKPORT HEADLANDS: This is one of the most unique diabase dikes in eastern Massachusetts, if not New England. Modal and chemical analyses are listed in Tables 1 and 2 respectively. The dike contains abundant plagioclase megacrysts up to at least 9.2 cm in length which increase in abundance and average size toward the interior of the dike where they account for approximately 35% (megascopic estimate) of the rock volume. In thin section, the center of the dike contains 53.1 volume percent plagioclase phenocrysts and megacrysts (Table 1). The grains are relatively fresh with some cores severely saussuritized and sericitized. A prominant joint occurs about 35 cm in from the east contact in parallel to it. Plagioclase phenocrysts up to 15 mm long make up less than 5 to 10 percent of the volume of the chilled zone bounded by this joint and the dike contact. About 50 cm farther into the dike a second prominant joint is present and parallel to the dike trend. The rock between these two joints is courser with phenocrysts up to about 27 mm accounting for 10 to 20 percent of the rock. From here inward, megacryst size and abundance increase to the maximums at the dike's center mentioned above. This distribution of megacrysts and phenocrysts is in agreement with that expected to be produced by flowage differentiation.

The dike strikes N 14° W and dips 88° E here and is also exposed below the parking lot at the end of Bearskin Neck across Rockport Harbor. Note this is an apparent left-lateral offset and one could hypothesize a fault trending through the harbor but such evidence is shaky at best without a visible fault. The dike can also be seen in the distance across Sandy Bay in Pigeon Cove where it is 8 m thick, trends N 27° W and dips 74° E. This locality is also slightly offset to the west from the more southern exposures.

A 6.0 cm thick aphanitic mafic dike cuts the megacryst-rich diabase near the water's edge. The large relatively smooth surface on the granite a few meters to the west was produced by erosion stripping of this thin dike.

End of field trip. Return south to Route 128 for connections north and south. A scenic route around Cape Ann via Rte. 127 also returns to Rte. 128 (7.7 miles) if you have time.

FELSIC VOLCANIC UNITS IN THE BOSTON AREA, MASSACHUSETTS

Richard S. Naylor
Earth Sciences Department
Northeastern University

INTRODUCTION

Felsic volcanic rocks are widely exposed in the Boston, Massachusetts, area. The Middlesex Fells Volcanics and the Lynn Volcanics occur to the north. The Mattapan Volcanics are exposed in the western and southern parts of the Boston Basin. The Blue Hills Volcanics (sometimes mapped as Mattapan Volcanics) crop out in the Blue Hills highlands south of Boston. The rocks are highly compacted and pervasively recrystallized, but they display numerous primary volcanic structures and textures and are nowhere metamorphosed to higher than chlorite grade. The rock units are well described in the references cited. This paper is concerned chiefly with a discussion of the age relationships, and is based substantially on two Masters' theses, Sayer (1974) and Zarrow (1978), supervised by the author.

Kaye and Zartman (1980) report a zircon age of 570 m.yr. from the Mattapan Volcanics. They interpret this as indicating a Late Precambrian age for the Mattapan Volcanics, and suggest on the basis of field relationships that other felsic volcanics in the Boston area may be similarly old. Following Zarrow (1978) the author will argue that the Lynn Volcanics at Pine Hill (Stop 4) are Precambrian, and will suggest the same for the Blue Hills Volcanics. Before 1976 most geologists accepted the interpretation that the felsic volcanics were Carboniferous (Emerson, 1917; Billings 1929), although LaForge (1932) and Naylor and Sayer (1976) had suggested the volcanics might be as old as Silvro-Devonian.

BLUE HILLS AREA

Stops 1 through 3 will show relationships typical of those used to establish the relative ages of rock units south of the Boston Basin. The author believes the sequence of units is as follows:

Wamsutta Formation (Carboniferous)
Blue Hills Porphyry = Quincy Granite (Ordovician)
Braintree Argillite (Middle Cambrian)
Blue Hills Volcanics (?Late Precambrian).

The Wamsutta Formation and Braintree Argillite are reliably dated by well-preserved fossils. The Quincy Granite has been dated at 430 to 460 m.yr. by Zartman (1977; U-Th-Pb zircon data). (Naylor and Sayer (1976) argued that earlier zircon data could be consistent with a Silvro-Devonian age for the Quincy Granite. Zartman (1977) reports new analyses with improved precision, and the author agrees with his conclusion that the Quincy Granite is most probably an Ordovician intrusive.)

Warren (1913) demonstrated that the Quincy Granite and the Blue Hills Porphyry are closely similar in mineralogy and major element chemical composition. This is unlikely to be coincidental inasmuch as the chemistry of both is distinctively alkalic and the modes of both include distinctive minerals like riebeckite, fluorite, and astrophyllite. Sayer (1974) demonstrated that the two units also yielded distinctively similar rare earth element "fingerprints." The two units are almost certainly co-magmatic and for the most part, the Blue Hills Porphyry can be considered as a finely-crystalline border phase of the Quincy Granite. Bottino and others (1970) published an Rb/Sr whole-rock isochron for the Blue Hills Porphyry with an age of 282 ± 8 m.yr. Sayer (1974) and Naylor and Sayer (1976) argue that the isochron age is anomalously young, and does not comprise a strong argument for a Blue Hills Porphyry younger than the Quincy Granite.

The contact between the Carboniferous Wamsutta Formation and the Blue Hills Porphyry is best exposed at Stop 1. Following Sayer (1974) and Naylor and Sayer (1976) the author concludes that the Wamsutta Formation rests nonconformably on an older Blue Hills Porphyry. The contact is not a simple one, however, and has been variously interpreted in the past. (In a group visit it is instructive to see how many alternatives can be entertained!)

Stop 2 displays porphyritic rocks that are clearly intrusive into and younger than the Middle Cambrian Braintree Argillite. The locality is very close to the main body of the Quincy Granite, and although the dike rocks are not typical of the Quincy Granite, relationships such as these are widely accepted as demonstrating that the Quincy is younger than the Braintree Argillite. The relationships described in these two paragraphs are consistent with the present fossil and isotopic dates.

The relationship of the Blue Hills Volcanics to the other units is less reliably established. Warren (1913) and most subsequent geologists have concluded that the Blue Hills Volcanics are older than the Blue Hills Porphyry and Quincy Granite. Stop 3, where the volcanics can be interpreted as screens enclosed in the porphyry, shows relationships typical of those on which this conclusion is based. Most workers have tacitly assumed that the volcanics are closely related to the granite and porphyry -- all three units comprising the "Blue Hills Igneous Complex."

If other felsic volcanics in the Boston area are as old as Precambrian, the author knows of no reason why the Blue Hills Volcanics cannot also be Precambrian. Chute (1969), who is responsible for the primary mapping of the Blue Hills could find no distinction between the Mattapan and Blue Hills Volcanics and mapped both as Mattapan. The Blue Hills Volcanics do not have the distinctive mineralogy or alkalic chemistry of the Quincy Granite and Blue Hills Porphyry, hence there is no proof of correlation with those units. The direct relationships demonstrate that the Braintree Argillite and the Blue Hills Volcanics are both older than the Quincy Granite, but do not prove which of the two is the older. It seems entirely possible that the Blue Hills Volcanics are Precambrian country rock intruded by, but genetically unrelated to, the Quincy Granite.

PINE HILL AREA

The Fells Upland is separated from the Boston Basin to the south by the Northern Border Fault. The fault dips to the north. Along it older, mostly igneous rocks of the Fells Upland have thrust upward and southward over the predominantly sedimentary rocks of the Boston Basin. The major rock units of the Fells Upland are the Dedham Granodiorite, the Middlesex Fells Volcanics, and the Westboro Quartzite. The Dedham Granodiorite has been dated as Late Precambrian (Kovach, and others, 1977; Zartman and Naylor, in press), and intrudes the Middlesex Fells Volcanics and Westboro Quartzite.

The Pine Hill area, Stop 4, lies in the Fells Upland immediately north of the border fualt. The Dedham Granodiorite is well exposed there, but the main body of the Middlesex Fells Volcanics lies further north. A dismembered screen of Westboro Quartzite is exposed in a string of xenoliths within the Dedham Granodiorite at Pine Hill. From Pine Hill eastward, a unit of felsic volcanics, the Lynn Volcanics, crops out between the Precambrian terraine described above and the border fault. The age of the Lynn Volcanics has been a subject of controversy, and is discussed in the remainder of this section.

Most geologists have adhered to the conclusion of Emerson (1917) and Billings (1929) that the Lynn Volcanics are Carboniferous. Others, including LaForge (1932) and Naylor and Sayer (1976) have suggested that the Lynn Volcanics correlate with intermediate and felsic volcanics of Silurian and Early Devonian age that are widespread to the northeast (Newbury Volcanics and the Coastal Volcanic Belt in Maine). In either case, the contact between the Dedham Granodiorite and the Lynn Volcanics from Pine Hill eastwards was interpreted as an unconformity with the younger volcanics resting on an eroded surface on the older plutonic rokcs. Zarrow (1978) remapped the Pine Hill area and concluded that the Lynn Volcanics there are intruded by the Dedham Granodiorite and are therefore also part of the Precambrian terraine. Her arguments are discussed below and may be demonstrated at Stop 4.

Internal Stratigraphy.

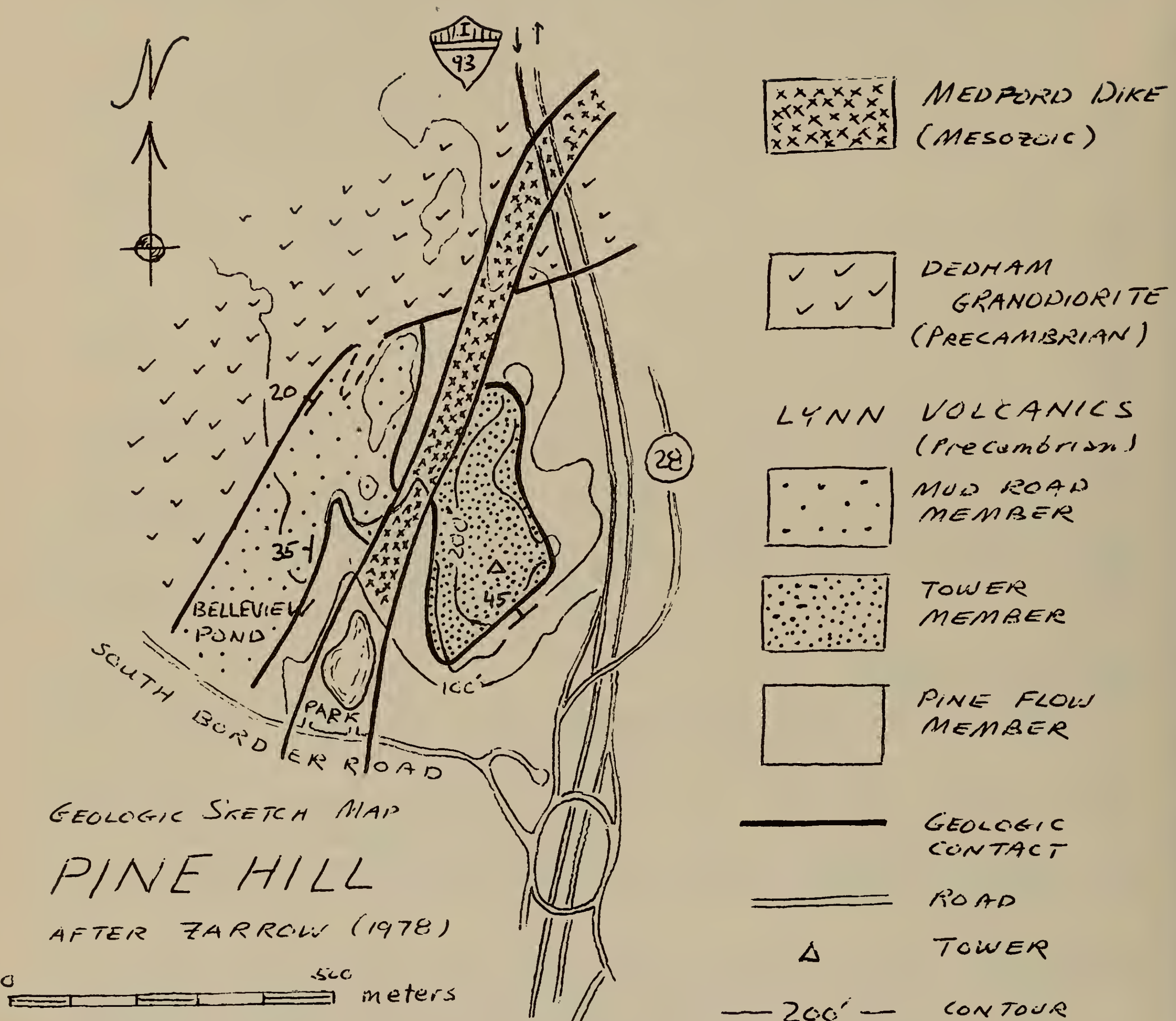
Zarrow (1978) was able to distinguish three local members within the Lynn Volcanics at Pine Hill (Figure 1). From east to west they are:

Pine Flow Member: pale grey-red to grey-green, uniform aphanitic matrix with abundant phenocrysts of quartz, K-feldspar, and plagioclase. Mafic minerals comprise about 2% of the rock and are conspicuous in hand specimens. The rock is locally brecciated, but xenoliths of other rocks are lacking.

Tower Member: dark grey aphanitic matrix with quartz and feldspar phenocrysts locally abundant. Xenoliths are locally abundant and are a distinguishing feature of the member. Some are probably altered, flattened pumice fragments; others appear to be xenoliths of volcanic material and of orthoquartzite. Banding is prominant around some of the xenoliths.

Mud Road Member: dark grey to dark grey-brown aphanitic matrix with phenocrysts of plagioclase, K-feldspar, and quartz. Near the granodiorite the matrix is strongly recrystallized and on some weathered surfaces the rock is hard to distinguish in hand specimen from the Dedham.

As shown in Figure 1, the contacts between the units are irregular. They do not appear to be conformable to the contact with the granodiorite. Rather, it seems more likely that they strike into the Dedham Granodiorite and were truncated by its intrusion.



GEOLOGIC SKETCH MAP

PINE HILL

AFTER ZARROW (1978)

FIGURE 1

Xenoliths in the Dedham Granodiorite

Xenoliths, ranging up to several meters across are common in the Dedham Granodiorite at Pine Hill. Most of the xenoliths are very fine-grained and most contain quartz as a very conspicuous mineral. Many of the xenoliths are of orthoquartzite. A string of these xenoliths north of Pine Hill may be a dismemebered screen of Westboro Quartzite. Thin section study shows that about half of the xenoliths are of felsite -- slightly more recrystallized, but otherwise similar to the Lynn Volcanics. Since most of the felsites contain abundant quartz in both matrix and phenocrysts, quartz is very conspicuous in the felsic xenoliths. When viewed as lichen-covered outcrops in the dark woods it is very hard to distinguish the xenoliths of felsite from those of orthoquartzite, but the eye can be trained to do this by practicing on xenoliths that have been identified in thin section. No clasts of granodiorite have been identified in the Lynn Volcanics.

Zarrow (1978) and the author interpret the felsic xenoliths as xenoliths of older Lynn Volcanics in a younger, intrusive Dedham Granodiorite.

Contact Relationships

The contact between the granodiorite and the volcanics dips 20 to 40 degrees NW. It would thus have to be strongly overturned if the Lynn Volcanics were interpreted as a younger unit resting unconformably on the Dedham. As the contact is approached, the Dedham Granodiorite becomes locally more finely crystalline (chilling?) and the Lynn Volcanics become more coarsely crystalline (contact metamorphism?). Northwest of Pine Hill is a possible dike of fine-grained granite penetrating the Lynn Volcanics.

All of these relationships seem more plausible if the Lynn Volcanics at Pine Hill are an older unit intruded by a younger Dedham Granodiorite. Given the age of the Dedham, the Lynn Volcanics at Pine Hill must be no younger than Late Precambrian.

Trace Element Studies

Zarrow (1978) studied the trace element distribution in samples of the Lynn Volcanics and Dedham Granodiorite at Pine Hill. Samples were analyzed for comparison from the Middlesex Fells Volcanics, the Mattapan Volcanics, and the Newburg (Silurian) Volcanics. Among her conclusions are the following:

1) All but one of the samples show "normal" granitic rare earth element (REE) distributions -- enrichment by 100 to 200 in La dropping with increasing atomic number but leveling off at 10 to 20 for the heavy REE (Tb to Lu).

   The exception was the Middlesex Fells sample which showed a flat (little fractionated) enrichment of about 25 across the REE spectrum. This sample, with a color index of 20, is more mafic than the others.

2) Using both major and trace element data it is possible to construct "liquid descent" models relating the Lynn Volcanics and the Dedham Granodiorite.

3) Three samples from the Pine Flow Member showed REE "fingerprints" that were identical within experimental error. The Mud Road Member shows distinctly greater enrichments and more variability between samples but has an REE pattern similar in shape to the Pine Flow samples. Differences in the REE data correlate with the criteria used to distinguish the two units in the field.

4) One felsic xenolith from the Dedham Granodiorite at Pine Hill was analyzed. It yielded an REE "fingerprint" identical to that of one of the Mud Road samples and identical to the Pine Flow samples except for slightly less depletion of Eu.

5) Of the comparison samples, the Mattapan Volcanics showed an REE pattern identical to the Pine Flow Member. The Newbury Volcanic sample was similar but showed much greater Eu depletion.

6) The REE pattern for the Lynn and Mattapan samples are very different from the pattern determined for the Quincy Granite (Buma and others, 1971) and the Blue Hills Porphyry (Sayer, 1974).

AGE OF THE BOSTON BAY GROUP

The Roxbury Conglomerate and Cambridge Argillite are the major formations in the Boston Bay Group. To the south, the Cambridge overlies the Roxbury and the two units are separated by the Squantum "Tillite". To the north, the Cambridge appears to interfinger with the Roxbury. Some volcanics (mostly mafic) interfinger with basal Roxbury Conglomerate. At most localities where the base of the Roxbury is exposed, the Roxbury rests unconformably on felsic volcanics or on Dedham Granodiorite. Following the determination by Bailey and Newman (1978) that the "Roxbury tree trunk fossils" are most probably sandstone dikes, no fossils are recognized from the Boston Bay Group. This means that the age must be determined indirectly.

Given the unconformities at its base, the Boston Bay Group cannot be older than the felsic volcanics and the Dedham Granodiorite. Emerson's (1917) assignment of an Acadian age to the Dedham is a major reason why the Boston Bay Group has conventionally been dated as Carboniferous. Proximity to the well-dated Norfolk and Narraganset Basins of Carboniferous age has also been a factor in this assignment, as were attempts to date the now-discredited "Roxbury tree-trunk fossils," but the sedimentary facies of the Boston Basin are not notably similar to those of the other basins. Billings (1929) lowered the age of the Dedham Granodiorite to Precambrian (eventually confirmed by isotopic dates), but did not regard this as cause to question the age of the overlying units. Naylor and Sayer (1976) suggested that the felsic volcanics might be Siluro-Devonian (correlation with the Newbury Volcanics and with the volcanics of the Maine Coastal Belt), and noted this would allow the Boston Bay Group to be as old as Devonian.

At present, the author knows of no proof that any of the felsic volcanics underlying the Boston Bay Group are younger than Late Precambrian. Given the lack of fossils (despite 150 years of geologic study) there appears no reason why the Boston Bay Group itself (at least in part) might not be Late Precambrian as proposed by Kaye & Zartman (1980).

On field trips to Newfoundland, the author has been impressed by lithologic similarities of the Cambridge Argillite and the Conception Group, the

Roxbury Conglomerate (plus underlying felsites) and the Harbour Main Volcanics, and the Dedham Granodiorite and the Holyrood Granite. Although designated "volcanics," the Harbour Main consists of both porphyritic felsites and polymict red conglomerates with clasts of granodiorite, felsite, and orthoquartzite. The stratigraphic sequence for the Avalon Peninsula, Newfoundland (King, 1980), seems remarkably similar to that of the Boston Basin, including the presence of tillite between the Harbour Main and the Conception group. The author was particularly impressed by relationships he was shown at Bacon Cove near Colliers, Newfoundland. There, banded argillites of the Conception Group are thrown into gently undulating folds and lie unconformably beneath Hyalithes bearing, red, silty limestone of Early Cambrian age. If correlations with the Avalon are precisely valid, this would suggest a Late Precambrian age for the bulk of the Cambridge Argillite.

It has by no means been demonstrated that all felsic volcanic rocks in the Boston Area are older than the Dedham Granodiorite. The literature contains numerous references to felsic volcanics lying unconformably above the Dedham or interbedded with sediments that contain Dedham clasts. It seems very likely that some felsites postdate the Dedham Granodiorite, but even these could be Precambrian. Siluro-Devonian intermediate and felsic volcanics are widespread along the southeast coast of Maine in a belt that includes the Newbury Volcanics of northeastern Massachusetts. It is at least possible that some felsic volcanics in the Boston area correlate with these, although all the known Siluro-Devonian volcanics appear to lie west of faults that connect with the Bloody Bluff Fault west of Boston.

AKCNOWLEDGEMENTS

Clifford Kaye first suggested to the author the possibility that the Boston Bay group and underlying felsites might be Cambrian or older. He and David Roy introduced the author and students to the geology of the Pine Hill area.

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ROAD LOG

The official trip will assemble at the University of Rhode Island, Kingston. Drive towards Boston on I-95 then turn eastbound (South Shore) on Route 128. Persons starting the trip from Boston may drive south on the Southeast Expressway and turn westbound on Route 128. (The exit to the first stop can be made from either direction off 128).

Junction Routes 28 and 128; exit to Route 28 northbound. A few hundred yards north of the interchange turn right into a small parking area in the woods alongside the road.

0.0 STOP 1 CONTACT BETWEEN THE BLUE HILLS PORPHYRY AND THE PONDVILLE CONGLOMERATE MEMBER OF THE WAMSUTTA FORMATION.

Walk back along the west side of Rt 28 and up the access ramp to the NW clover leaf of the Rt 28-128 Interchange. The cut which exposes the contact was built after Chute (1969) had completed most of his field mapping; it is one of the more controversial exposures in the Boston area.

Briefly examine the Blue Hills Porphyry, then work your way fairly quickly along the outcrop until you are well up into the Pondville Conglomerate. Now decide where you would put the contact between the two units (in a group it is instructive to put this to a vote).

The PONDVILLE CONGLOMERATE is the basal unit of the Norfolk Basin sequence, the higher members of which contain Carboniferous fossils. The conglomerate (here called the Giant-Pebble Conglomerate) contains clasts of Blue Hills Porphyry, felsite (presumably Aporhyolite), quartzite, and argillite. Clasts of normal Quincy Granite have not been reported, although clasts of fine-grained hornblende granite can be found. At the top of the section the clasts are well-differentiated from the matrix, and lower in the section one can find an irregular but discrete surface below which the clasts no longer "pop out" from the matrix. Most workers, ourselves included, regard this surface as a non-conformity separating the Carboniferous Pondville Conglomerate from an older Blue Hills Porphyry.

This leaves a curious zone with pseudo-cobbles (greenish spheroids of microperthite, quartz porphyry in a matrix of generally finer-grained reddish porphyry) separating the Pondville from the normal, massive variety of the Blue Hills Porphyry. Chute interpreted this as a zone of spheroidal weathering and residual soil below the non-conformity.

D.R. Wones drew our attention to features suggesting a certain amount of transport of the pseudo-cobbles. They differ from each other and from the matrix in the details of phenocryst abundance and composition, in such a way that it appears unlikely that all the differences could be caused by weathering. He raised the possibility that the porphyry at this locality might be a Carboniferous volcanic unit grading upwards into the true conglomerate through a zone containing volcanic clasts in a welded volcanic matrix, the outcrop possibly having formed as a lahar.

If time and interest permit, one may see the overlying Wamsutta Formation on the opposite side of Route 128. Return to Route 28 and walk through the underpass, skirt the fence then backtrack to walk along the canal to the Wamsutta roadcut in the exit loop. Note the cross-beds, channel-fill, and other sedimentary features, and study the oxidation-reduction reactions represented in the red and green coloration. Can you decide if the reduced zones (green) are localized around carbon-rich plant-fragments?

RETURN to cars and drive NORTH on Rt 28 (Randolph Ave)

1.1 Jct. Randolph Ave and Chickatawbut Road, CONTINUE north on Randolph Ave. past golf course.

2.3 PARK on right at gravel road (don't block) opposite yellow & white house on left. Walk about 200 meters (yards) SE on the gravel road then up hill (north) on a poorly marked trail. The hill is overgrown with brambles, making it worthwhile to locate the trail. Look for ledges off the trail just below the brow of the hill and for adjacent outcrops on the flat summit.

STOP 2 RHOMB PORPHYRY AND BRAINTREE ARGILLITE

The outcrops along the slope of the hill are hornfels representing the Middle Cambrian BRAINTREE ARGILLITE. This unit has yielded some of the largest trilobites known, Paradoxides harlani. These are Acado-Baltic fossils whose faunal-province relationships are part of the evidence for the closing of the Iapetus ("proto-Atlantic") Ocean during the evolution of the Appalachian Mountains. It is generally agreed that the Braintree Argillite occurs as xenoliths and roof-pendants in the Blue Hills Igneous Complex, which is thus younger than Middle Cambrian. At this locality the Braintree Argillite is cut by diabase dikes that appear to be older than the Quincy Granite. Further uphill is a 30 m wide apophysis of fine-grained Quincy Granite with abundant inclusions of rhomb-porphyry and argillite, and at the top of the hill is the main body of the Quincy Granite marked by abudnant inclusions and an intrusion breccia.

2.3 RETURN to cars. U-TURN and return south on Randolph Ave.

3.5 Jct Randolph Ave and Chickatawbut Road. TURN LEFT on Chickatawbut Road. Pavement outcrops at the SE corner of the jct. are Blue Hills Porphyry and were described as Stop 5 of Naylor and Sayer (1976).

4.8 Blue Hills Reservoir on right.

5.0 PARK on RIGHT or LEFT in small parking areas.

STOP 3 BLUE HILLS PORPHYRY AND BLUE HILLS VOLCANICS
(APORHYOLITE is a local synonym for the Blue Hills Volcanics)

STOP 3A Walk back to the junction of Wampatuck and Chickatawbut Roads, then south on trail (old road) about 100 meters (yards). To the left is a rock-knob with a vertical face on the south side; examine the face. The knob is mostly Blue Hills Porphyry but the face shows a fine-grained rock that is probably a screen or large inclusion of APORHYOLITE. Examine the porphyry on the top of the knob; the aphanitic matrix characteristic of the porphyry is more evident here than at the previous stop. The porphyry appears chilled against the Aporhyolite.

STOP 3B Return to cars and follow trail south to summit of rock-knob. On the way up you cross a thin screen of Aporhyolite in the porphyry and one can closely approach a contact on the south side of the screen. The porphyry on the summit of the knob contains digested xenoliths of the Aporhyolite.

STOP 3C Return to parking area and follow trail north of raod to summit of Wampatuck Hill. (Take LUNCH to eat on summit with good views over Boston.) The trail uphill is mostly in Blue Hills Porphyry then crosses a contact into the APORHYOLITE, which crops out on the top of the hill. The volcanics (Aporhyolite) here were designated by Kaktins (1976) as the Wampatuck Hill Ash Flow, which he subdivided into the following units: a basal clastic-rich eutaxitic zone; a densely-welded zone with few phenocrysts and few spherulites; a eutaxitic zone with abundant flattened pumice; and an upper phenocryst-rich zone with minor, but relatively uncompressed pumice. The uppermost unit is the one in contact with the porphyry, the probable top of the flow having been cut out here; down-section is to the north at this locality. (Kaktins, 1976; Geol. Soc. Amer Memoir 146)

5.0 RETURN to cars. CONTINUE EAST on Chickatawbut Road.

5.1 TURN LEFT (north) onto Wampatuck Road

5.6 Small quarry in woods on left exposes the contact between the BLUE HILLS PORPHYRY and the QUINCY GRANITE. Warren (1913) designated this the type locality for the porphyry and the locality is described as Stop 2 of Naylor and Sayer (1976).

6.2 Merge (straight) onto Willard St.

6.3 Jct. with Southeast expressway. Continue (more or less straight ahead) under the expressway then turn LEFT onto ramp and enter Expressway NORTHBOUND (towards Boston).

(Mileages beyond this point have not been logged.)

STAY on Expressway north past jcts. with Mass Ave. and the Mass Pike through the South Station Tunnel and downtown Boston. After leaving the tunnel, drive in the middle-left lane and follow signs for I-93 northbound. About ½ mile north of North Station/Boston Garden, CONTINUE STRAIGHT from the left or center lanes to pick up I-93 while much of the traffic veers right onto I-95 and the Mystic (Tobin) Bridge. (Just before this jct. traffic enters from the left and many of these cars want to cross to the right; don't let them push you so far to the right that you can't get onto I-93!)

A mile or two north of the jct watch on your left for Somerville Lumber, then a church, then the Somerville Housing Project. A low quarry wall back of the project is the best surface exposure of the Cambridge Argillite. From here, Pine Hill (woods with stone tower) should be visible ahead on the left.

The exit to Pine Hill is shown on Figure 1; it is just before the base of the hill. The exit from I-93 should have signs to Rt 28 north. Cross over the interstate and exit the rotary onto South Border Road. Turn RIGHT into the small parking area at Belleview Pond. Lock cars.

STOP 4 DEDHAM GRANODIORITE AND LYNN VOLCANICS AT PINE HILL

Figure 1 is a sketch map after Zarrow (1978) by the geology at Pine Hill. Participants on the trip will be given a more detailed base-map showing contours, trails, etc. (Pine Hill is popular as a mapping exercise for colleges in the Boston Area, and the author is reluctant to publish a "solution" showing contacts on the detailed base-map.) The descriptions ignore the Medford and other mafic dikes which are described elsewhere in this guidebook by M.E. Ross.

a. Follow the trail E from Pond skirting base of Pine Hill to large cuts along I-93. The first cut exposes the homogeneous Pine Flow Member of the Lynn Volcanics cut by mafic dikes and by a few dikes of felsite breccia. The further, lower cut exposes the contact between the Lynn and the Dedham. Adjacent to the contact is a finely crystalline granite (chilled Dedham?). The Dedham contains numerous xenoliths, mostly of quartzite. A further, small cut shows interesting interactions between the Dedham and the mafic Medford Dike. From here, scramble up to see the Dedham-Lynn contact and the xenoliths from the top of the second cut.

b. Worm under the fence and follow the contact west about 100 yards, crossing the Medford Dike. Outcrops accessible from the trails to the north expose numerous xenoliths of felsite and quartzite. (See text for significance of the felsite xenoliths and the problem of identifying them in the field.)

c. Follow broad trail SE to summit of Pine Hill. Familiarize yourself with the characteristics of the Tower Member of the Lynn Volcanics (see text), then attempt to trace contact with Pine Flow Member on the south side of the hill. Look for stratification. Return to Pond.

d. Trails NW from the Pond cross the Mud Road Member of the Lynn Volcanics (see text). Try to identify and follow the contact with the Dedham Granodiorite. (As discussed in the text, the two units are distinct in thin section, but many weathered surfaces on the volcanics are easily confused with those of the granodiorite.)

ZIRCON GEOCHRONOLOGY AND PETROLOGY OF PLUTONIC ROCKS IN RHODE ISLAND

O. Don Hermes,[1] L.P. Gromet,[2] R.E. Zartman[3]

INTRODUCTION

The geological evolution of the plutonic basement of Rhode Island and adjacent areas is complex and poorly understood. The basement, which is composite in nature, is dominated by late Precambrian calcalkaline plutonic rocks as well as by alkaline and calcalkaline rocks of mid-Paleozoic age. In addition, some of these rocks in southernmost Rhode Island are intruded by late Paleozoic calcalkaline plutonic rocks. Rocks that form the older basement have several features in common with the rocks underlying the Avalon Pennisula of Newfoundland and other areas along the eastern margin of the Appalachians. Recognition of this similarity has led to growing acceptance of the hypothesis that these areas constitute a distinctive belt within the Appalachian Orogen. Known as the Avalon Zone, this belt is characterized by a basement of late Precambrian plutons intruded into metasedimentary and metavolcanic rocks (Rast and others, 1976; Williams, 1978). These plutonic rocks probably represent the first major continental crust-forming event within the Appalachian orogenic cycle. An important aspect of occurences in southeastern New England is that a deeper level of erosion has created extensive exposures of the core of this part of the Avalon Zone; thus we are offered outstanding opportunities for study of intrusive rocks associated with the early developmental stage of the Appalachian Orogeny.

With the exception of the work by Day and others (1980a, b) on the Sterling Group, little petrographic or geochemical data are available for the older crystalline rocks of Rhode Island. Recognizing the potential significance of this terrain as it relates to the understanding of the Avalon Zone, we have initiated integrated geochronological, petrological, and geochemical studies of selected parts of the area. New petrographic and geochemical data, and zircon U-Th-Pb isotopic ages on a limited suite of these rocks are providing a needed framework for on-going studies. Outcrops visited on this trip will emphasize the diversity of lithologies, structures and relationships that must be studied in greater detail before a better understanding of the complex geologic history of the region can be developed.

PETROLOGY AND GEOCHRONOLOGY

Earlier studies summarized in Quinn (1971) and the Rhode Island state map outline and separate major lithologic units. In broad terms, Quinn defined three major groupings of igneous rocks: (1) "older" plutonic rocks thought to be of early or middle Paleozoic age (including the Ponaganset, Sterling, and Esmond Groups), (2) rocks of "Mississippian (?) or older" age (East Greenwich Group and Rhode Island "Quincy"), and (3) "Pennsylvanian or younger" rocks (Narragansett Pier and Westerly Granites). Few reliable radiometric ages have been determined on these rocks, and

[1] Department of Geology, University of Rhode Island, Kingston, RI 02881
[2] Department of Geological Sciences, Brown University, Providence, RI 02912
[3] U.S. Geological Survey, M.S. 963, Denver Federal Center, Denver, CO 80225

most age estimates have been based on crosscutting relationships and syn- or post-kinematic characteristics, such as, the degree of foliation. However, the degree of deformation is a poor indicator of age since, in general, all of these units are somewhat deformed, and it is common to observe rock units within a single outcrop grade from well-foliated to massive. Although several granitic rocks to the east have yielded Cambrian to late Precambrian radiometric ages (including the Bulgarmarsh Granite (Galloway, 1973), Newport Granite Porphyry (Smith, 1978), and Dedham Granodiorite (Kovach and others, 1977; Zartman and Naylor, in press)), these rocks are of unknown relationship to the rocks west of the Narragansett Basin.

Our preliminary petrologic and geochronologic work (see Fig. 1 for sample localities) indicates that some substantial revisions to Quinn's grouping of these rocks is required. In particular, the Scituate Granite Gneiss and perhaps other lithologies of the Sterling Group appear to be composed of compositionally and temporally diverse rocks which may not have a common origin. For the purpose of the presentation, we choose to discuss these rock units in terms of the following groupings: (1) Esmond Group, (2) mid-Paleozoic rocks, (3) Hope Valley and Ten Rod Granites, and (4) Narragansett Pier and Westerly Granites. This list is not in order of age, but does correspond to the NE to SW order that we will follow on this trip (Fig. 2).

ESMOND GROUP: These rocks range from quartz diorite to two-feldspar granite and are largely restricted to a north-south zone just west of the Narragansett Basin (Fig. 1). The Esmond Group also may include more mafic hypabyssal and volcanic rocks that are associated spatially with the Hunting Hill greenstone member of the Blackstone Series.

The Esmond Group rocks are massive to faintly foliated and generally exhibit prominent secondary development of chlorite, epidote, and muscovite. These minerals are concentrated along annealed brittle fractures and form a foliation in the rock. Minerals present include quartz, microcline, plagioclase, biotite, opaques and accessory sphene, apatite, monazite, zircon and calcite. Xenolithic inclusions and larger roof pendants of Blackstone Series-like rocks are common.

Age relationships within the Esmond Group show the Esmond Granite to be intrusive into quartz diorite, and both of these lithologies are cut by a fine-grained granite facies. Quinn (1971) described a porphyritic variety, the Grant Mills Granodiorite, as gradational into Esmond Granite.

Representative major element analyses of these rocks are given in Table 1, and selected oxides and trace elements are illustrated in Figures 3-5. These data and the petrography indicate that the Esmond Group is a calcalkaline rock series. Interestingly, rare earth patterns of some Esmond Group rocks are similar to those from other calcalkaline granitic suites known to have formed at a convergent plate boundary, such as the Peninsular Range batholith (Gromet, 1979; Gromet and Silver, 1979a, b) and the Sierra Nevada batholith (Frey and others, 1978).

The summary of zircon geochronology presented in Figure 6 shows that all sampled varieties of the Esmond Group have a late Precambrian primary age and can be interpreted to be comagmatic. This age is similar to a Rb-Sr isochron (Kovach and others, 1977) and to zircon ages (Zartman and Naylor, in press) for Dedham related rocks from nearby Massachusetts. The zircon fractions fall on a chord whose lower intercept trends toward zero, indicating no major isotopic disturbance

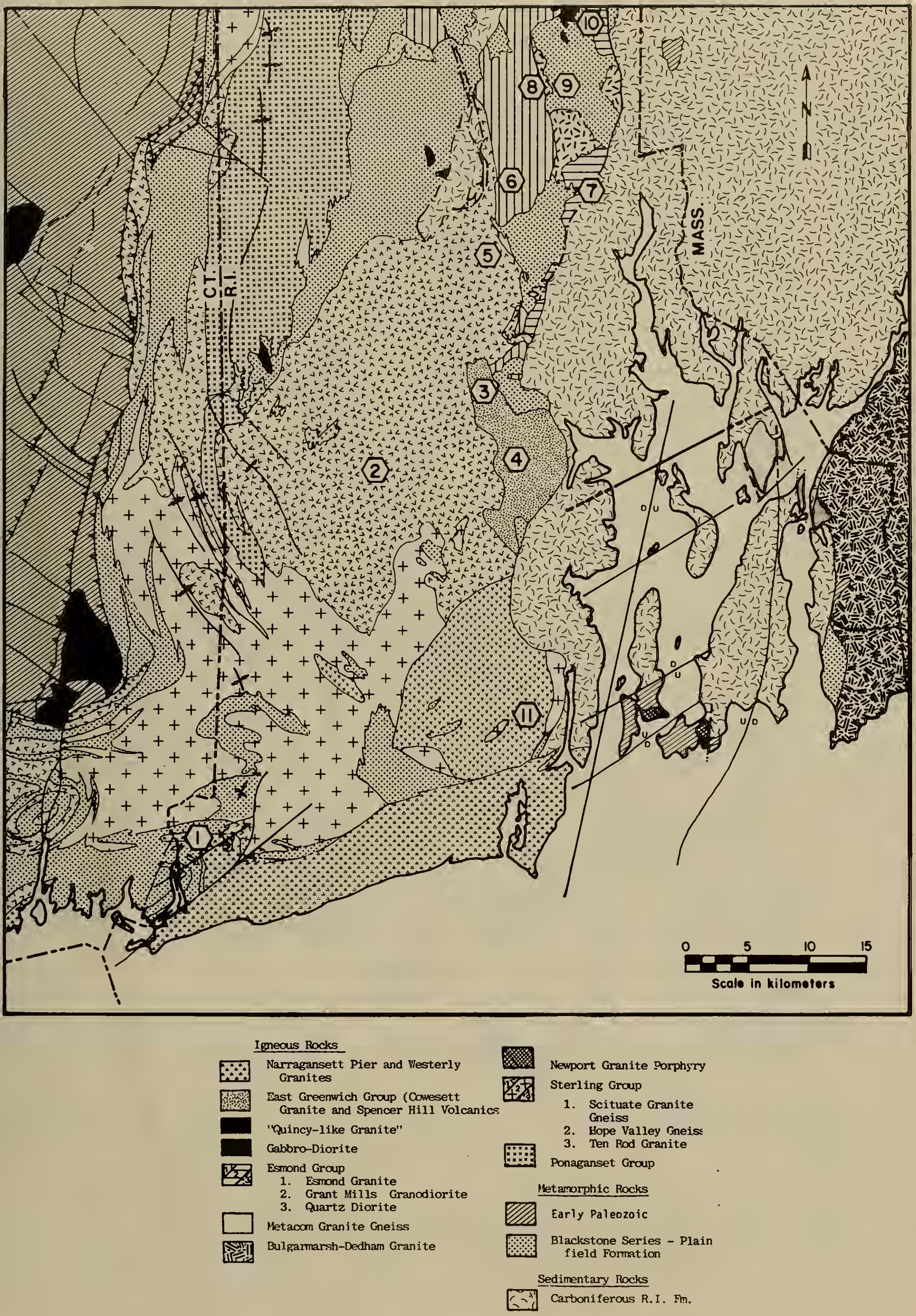

Figure 1: Generalized geologic map of Rhode Island and adjacent areas. Numbered hexagons indicate locations of samples collected for zircon analysis.

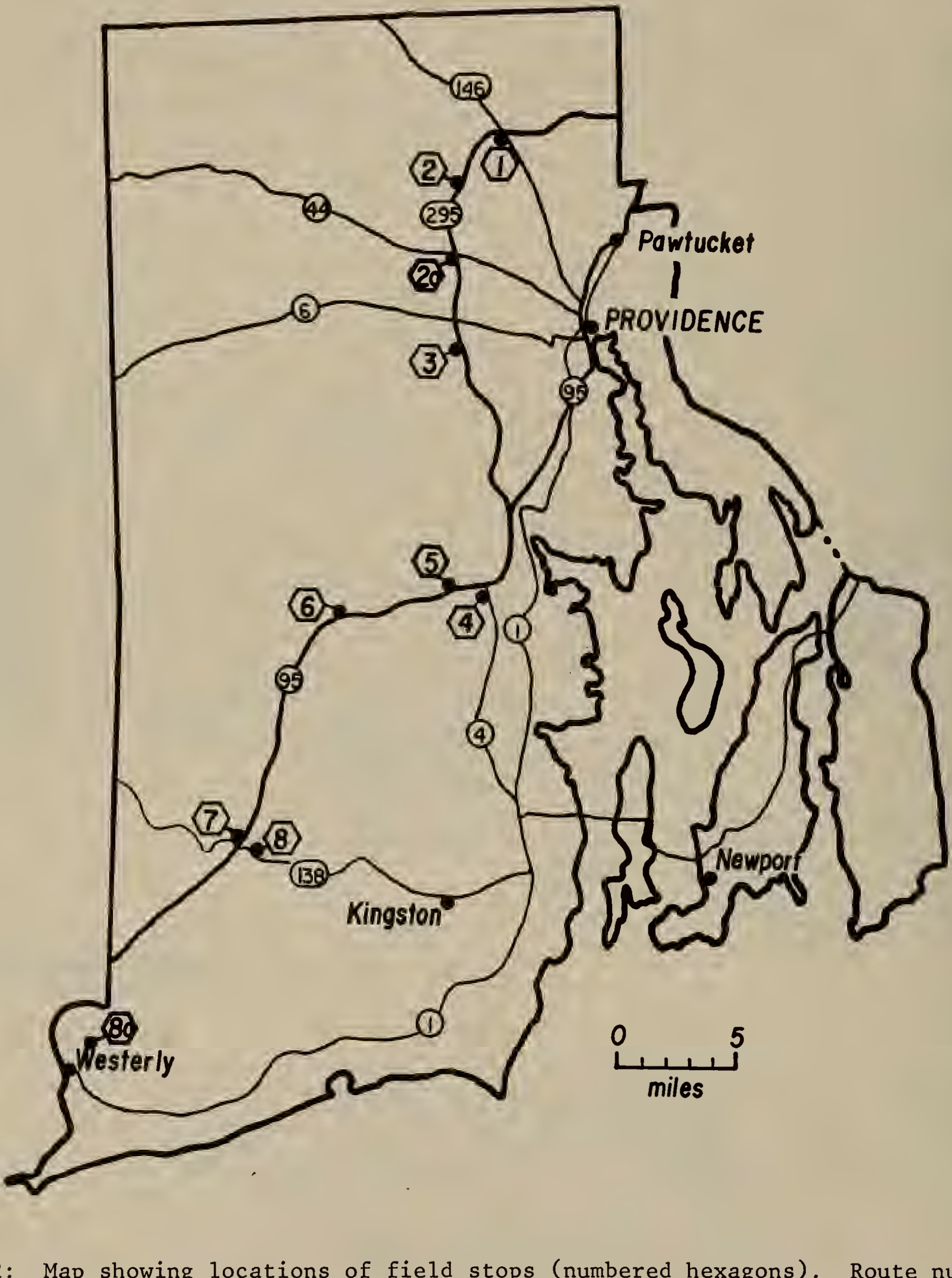

Figure 2: Map showing locations of field stops (numbered hexagons). Route numbers for major highways are given by numbers enclosed in circles or ellipses.

Table 1: Major element chemistry of selected plutonic rocks from Rhode Island.

	1	2	3	4	5	6	7	8	9	10
	RIQ	PCG	CG	SGG	EG	FEG	GMG	Qd	PSGG	TRG
SiO_2	70.24	74.78	75.64	73.84	74.48	74.34	72.46	65.02	73.5	73.0
Al_2O_3	9.80	11.43	10.49	10.44	11.98	12.86	12.42	17.54	12.9	13.6
Fe_2O_3	7.17	1.80	1.28	1.60	0.95	1.07	2.02	4.67	2.50*	2.98*
FeO	2.50	0.38	0.20	0.47	0.23	0.10	0.69	2.74		
MgO	0.06	0.08	0.05	0.06	0.28	0.29	0.27	1.34	0.30	0.56
CaO	0.58	0.56	0.54	0.30	0.96	1.33	1.58	3.98	1.21	1.51
Na_2O	5.26	3.54	3.72	3.38	3.74	2.98	3.86	3.50	3.28	3.21
K_2O	4.24	4.98	4.56	4.67	3.92	4.80	4.44	2.12	5.03	4.47
H_2O	0.46	0.31	0.81	0.43	0.34	0.53	1.04	0.18	0.77	0.29
TiO_2	0.17	0.16	0.02	0.06	0.13	0.14	0.38	0.78	0.26	0.31
P_2O_5	bd	0.01	bd	bd	0.02	0.02	0.07	0.14	0.05	0.08
MnO	0.14	0.04	0.02	0.03	0.04	0.04	0.05	0.09	0.05	0.07
Total	100.62	98.07	97.33	95.28	97.07	98.50	99.28	102.10	99.85	100.08
molecular $\frac{Na_2O + K_2O}{Al_2O_3}$	1.348	0.981	1.053	1.017	0.867	0.786	0.898	0.459	0.840	0.744
Q	25.20	34.97	37.55	37.89	36.44	35.95	30.49	25.85	32.33	33.35
C						.42		2.53		.93
OR	24.90	30.01	27.68	28.96	23.86	28.80	26.43	12.27	29.77	26.39
AB	26.64	30.54	29.35	29.07	32.60	25.60	32.90	29.01	27.14	27.80
AN		.60			4.45	6.57	3.48	18.44	6.96	5.63
AC	15.50		2.63	.83						
WO	1.19	.90	1.15	.65	.13		1.65		.02	
EN	.15	.20	.13	.16	.72	.73	.68	3.27	.75	1.39
FS	3.08		.05					.05		
MT	2.56	.91	.59	1.51	.51	.05	1.30	6.63	1.02	.94
HM		1.21		.35	.63	1.05	1.14		1.30	1.83
IL	.32	.31	.04	.12	.25	.27	.73	1.45	.50	.59
AP		.02			.05	.05	.17	.32	.12	.19
Total	99.54	99.68	99.17	99.55	99.65	99.46	98.96	99.83	99.23	99.72

Column:

Alkalic Rocks: 1 - Rhode Island "Quincy"; 2 - Perthitic Cowesett Granite; 3 - Coewsett Granite; 4 - "type" Scituate Granite Gneiss.

Calc-alkaline rocks: 5 - Esmond Granite; 6 - Fine-grained Esmond Granite; 7 - Grant Mills Granodiorite; 8 - Quartz diorite; 9 - Porphyritic Scituate Granite Gneiss; 10 -Ten Rod Granite.

* All iron reported as Fe_2O_3

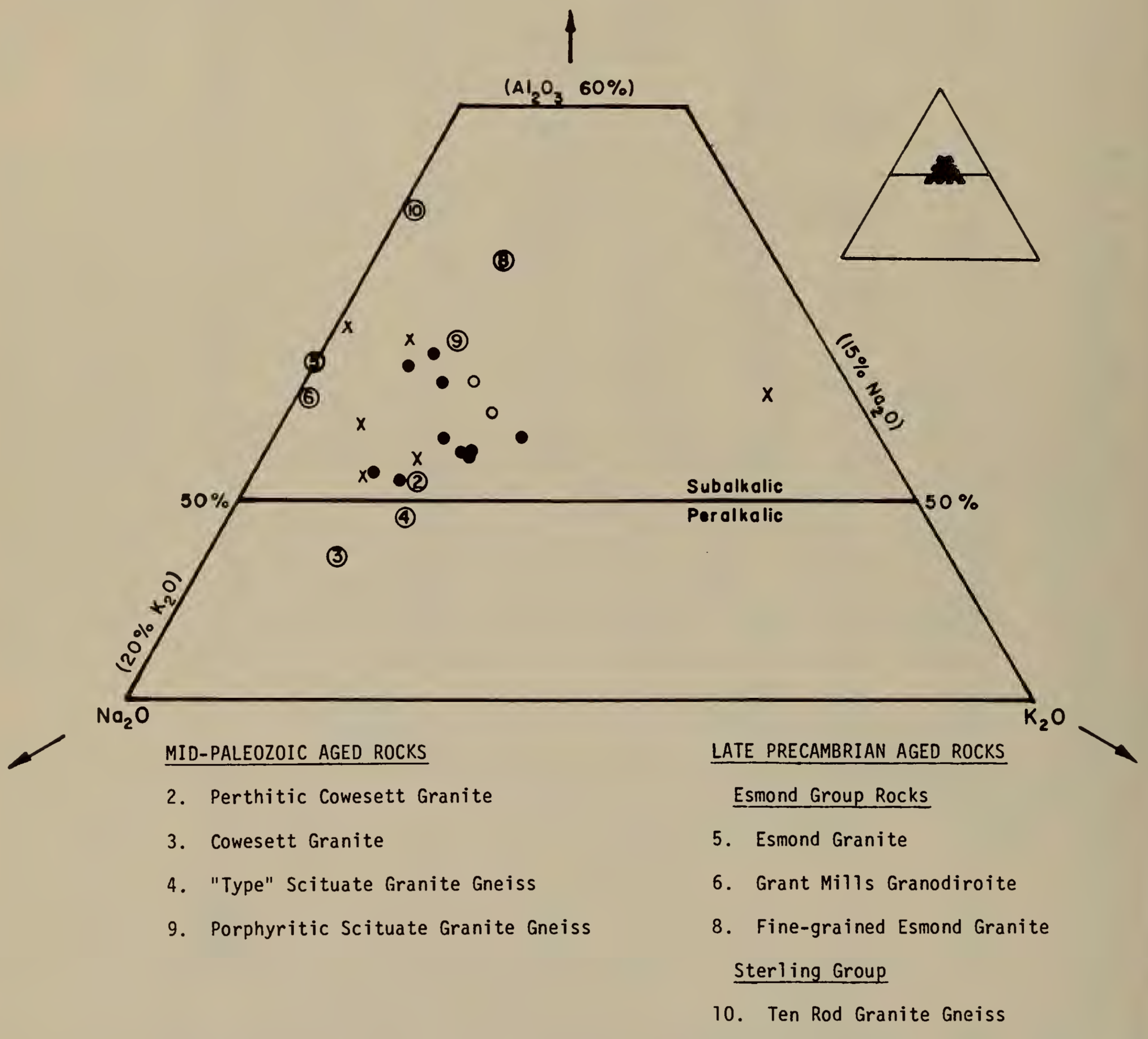

Figure 3: Plot of molecular Al_2O_3-Na_2O-K_2O for some granitic rocks from Rhode Island. Numbers correspond to analyses on Table 1 (analyses 1 and 7 plot out of this diagram). Data from Day and others (1980a) as follows: x = Hope Valley Alaskite Gneiss, o = Ten Rod Granite Gneiss, ● = Scituate Granite Gneiss.

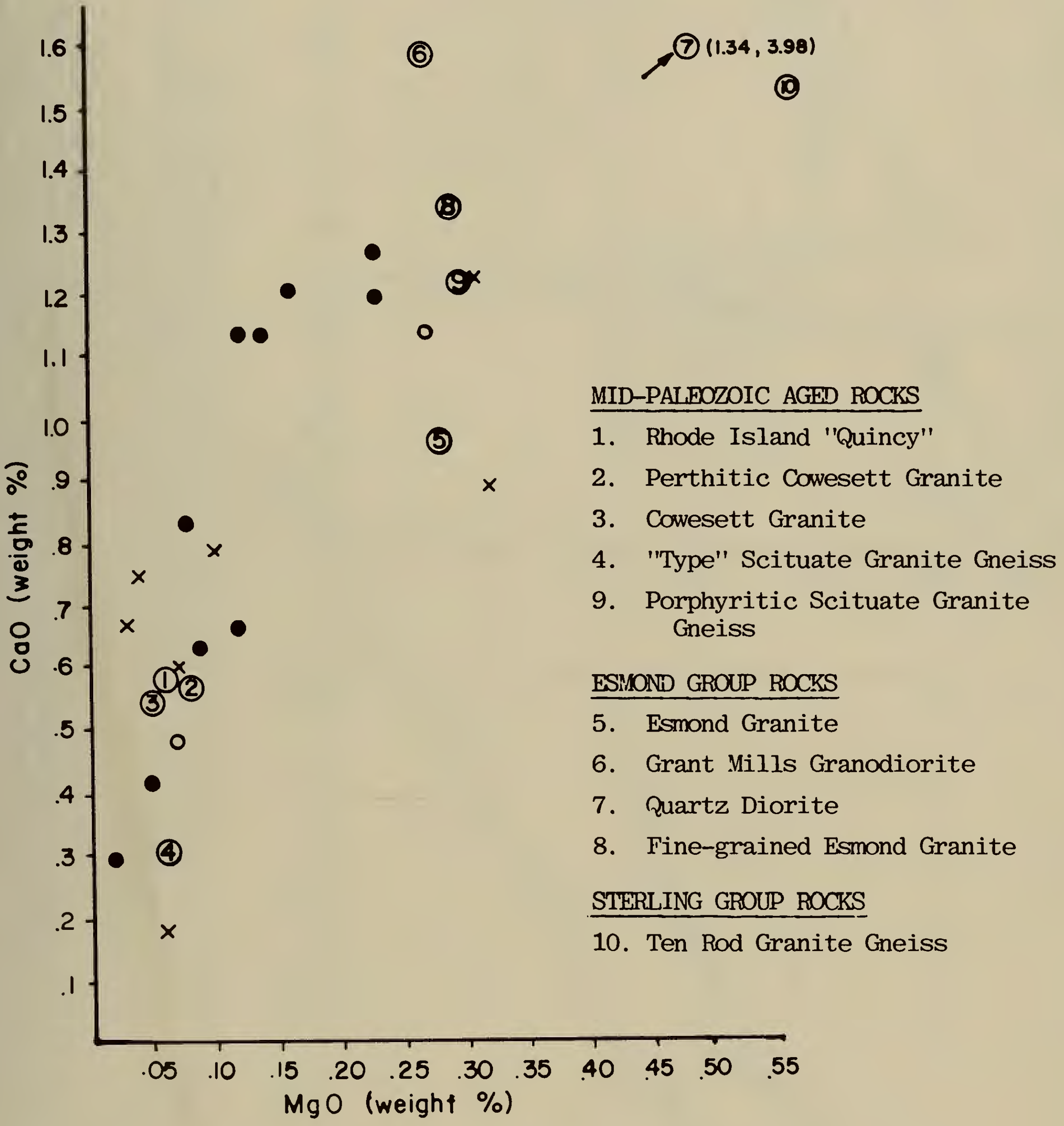

Figure 4: CaO *vs*. MgO for some granitic rocks from Rhode Island. Numbers correspond to analyses on Table 1. Symbols same as in Figure 3.

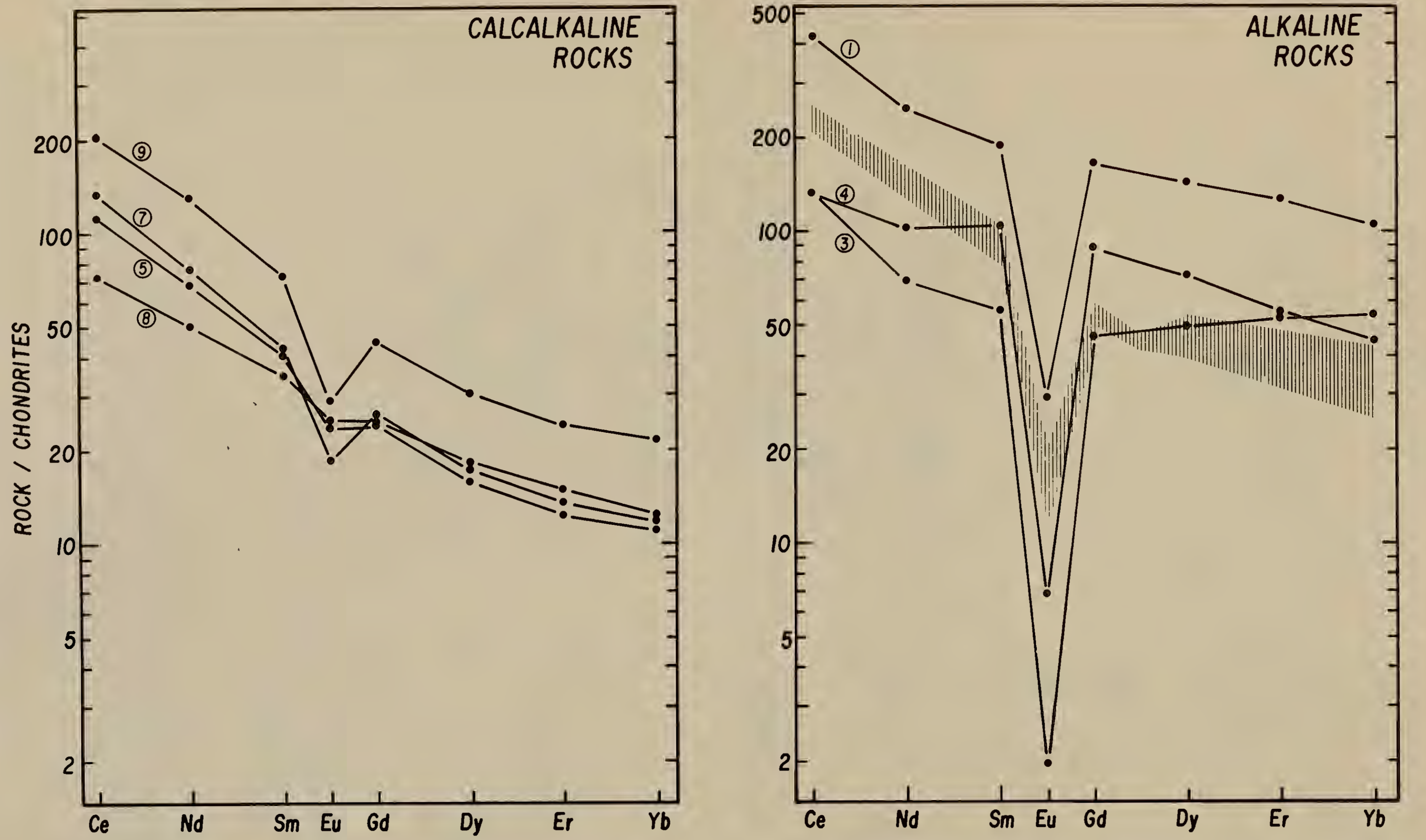

Figure 5: A. REE patterns of a few calcalkaline granitic rocks from Rhode Island. Numbers refer to samples in Table 1. The three lowermost patterns (5,7,8) are from rocks of the Esmond group of late Precambrian age. The sample with the highest REE concentrations (9) is part of the Scituate granite of mid-Paleozoic age.

B. REE patterns of a few mid-Paleozoic granites from Rhode Island and a field for rocks of similar age and composition from Massachusetts (Buma and others, 1971). There is a significant variation in the REE pattern shapes of these rocks, but as a group they have two distinguishing characteristics: (1) highly enriched REE contents, especially in the heavy REE, and (2) exceptionally large negative Eu anomalies.

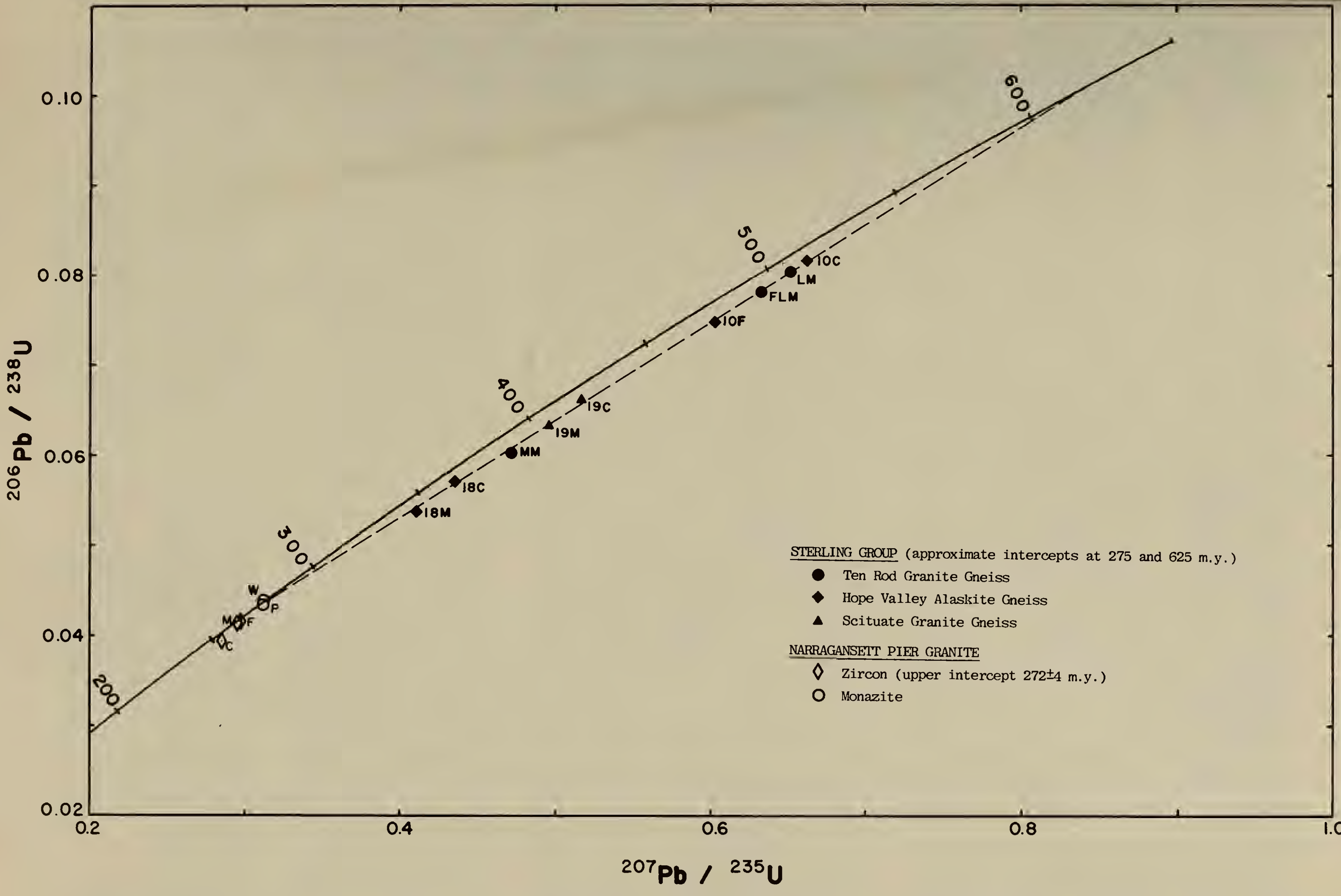

Figure 6: Concordia diagram showing distribution of zircon fractions for: (1) Esmond Group rocks, and (2) mid-Paleozoic rocks. Size fractions of zircons and characteristics as follows: C = 100-150 mesh, M = 200-250 mesh, F = 325-400 mesh, LM = least magnetic, MM = most magnetic, DB = dark brown, LT = light color.

other than a general modern day lead loss. This interpretation is supported by the feebly developed deformation and metamorphism in these rocks. In addition to similar ages, Esmond and Dedham related rocks also exhibit similar primary mineralogy, widespread late-stage or secondary development of chlorite and epidote, and a comparable tectonic fabric; possibly these two groups formed during the same magmatic episode.

MID-PALEOZOIC ROCKS: Our work has identified two groups of mid-Paleozoic rocks: the Cowesett Granite and related rocks of the East Greenwich Group, and at least part of the Scituate Granite Gneiss. The Cowesett Granite is an alkalic to peralkalic hypersolvus granite that contains biotite and accessory fluorite, and sodic amphibole and pyroxene. It grades from an equigranular and massive lithology to a rock which is porphyritic and massive to faintly foliated (the perthitic facies of Quinn, 1971). Quinn noted the presence of sparse riebeckite in some rocks of the East Greenwich Group and pointed out their possible affinity to alkalic rocks in northern Rhode Island (see Trip B-4) and to the Quincy Granite in Massachusetts. New analyses of East Greenwich rocks confirm this alkalic chemistry (Table 1, Figs. 3-5).

A significant observation of our early work is that much of the Scituate Granite Gneiss to the north and west of the East Greenwich Group likewise exhibits a hypersolvus texture, and alkalic mineralogy and chemistry (Table 1, Figs. 3-5). This alkalic character has not been recognized previously in spite of the available chemistry, nor with knowledge of the characteristic mineral assemblages and common mesoperthitic textures. The probable reason that the alkalic nature as well as their young ages were overlooked is that these rocks commonly are moderately foliated in distinct contrast to Cowesett Granite and to chemically and temporally similar rocks in Massachusetts and the Gulf of Maine (e.g., Zartman and Marvin, 1971; Lyons and Kruger, 1976; Hermes and others, 1978). However, not all of the Scituate rocks are distinct alkalic or peralkalic. For example, the Scituate variety exposed at our Stop 6 is a two-feldspar porphyritic rock that plots well into the subalkalic field (Figs. 2-3). Unlike more alkalic varieties, this rock lacks sodic pyroxene/amphibole, and contains substantial Ca-bearing minerals including plagioclase, epidote, and apatite.

Zircon age relationships for the alkalic rocks lie upon a well defined chord having upper and lower intercepts of 373 ± 7 m.y. and 17 ± 30 m.y., respectively (Fig. 6). The confirmation that mid-Paleozoic alkaline-peralkaline plutons occur in Rhode Island allows us to extend the trend of these rocks southward from known exposures in Massachusetts and the Gulf of Maine. At present we are uncertain as to the southern and western extent of these rocks in Rhode Island, but clearly they encompass a significant portion of terrain mapped formerly as Scituate Granite Gneiss, and they may also include portions of the Hope Valley Alaskite and Ten Rod Granite Gneisses (see discussion below).

An intriguing problem is presented by the fact that the distinctly subalkalic porphyritic facies of the Scituate Granite Gneiss at Stop 6 is the same age as the alkalic rocks (Fig. 6). Interestingly, reconnaissance observations of outcrops between this rock and the Cowesett Granite (Stops 4 and 5) appear transitional, and at Stop 6 the coarse-grained porphyritic rock grades into a finer-grained border zone variety. These field observations and the equivalent ages raise the possibility that the cores of the alkalic plutons may pass into more subalkaline lithologies at their margins. Alternate interpretations have to be evaluated, however.

An important objective of our continuing studies will be to sort out the petrologic and structural relationships of the Scituate and East Greenwich rocks. The new radiometric data does require re-evaluation of the previous grouping of some map units by Quinn, and therefore, the interpretations of some age relationships. For example, Quinn (1971) states that Esmond Granite intrudes the Scituate Granite Gneiss, whereas our work demonstrates that at least some of the terrain formerly mapped as Scituate Granite Gneiss is Devonian in age and several hundred million years younger than the Esmond Granite. On the other hand, zircon from a Scituate Granite Gneiss sample in Massachusetts just north of NW Rhode Island yields a late Precambrian age (Zartman and Naylor, in press). Therefore, it appears that the Scituate terrain may contain Precambrian rocks as well as the younger alkalic and subalkalic rocks. In light of the two age groups, it probably will be necessary to redefine the Scituate Granite Gneiss in future work.

HOPE VALLEY ALASKITE AND TEN ROD GRANITE GNEISS: Much of southern and western Rhode Island and adjacent parts of eastern Connecticut is underlain by Hope Valley Alaskite and Ten Rod Granite Gneisses, members of the Sterling Group (Fig. 1). The Hope Valley Alaskite Gneiss is a mafic-poor rock whereas the Ten Rod Granite Gneiss contains more biotite and opaques than either Hope Valley or Scituate Granite varieties. Commonly Ten Rod Granite Gneiss contains large phenocrysts of microcline up to several centimeters in longest dimension. Both the Hope Valley and Ten Rod rocks are well-foliated and appear to have undergone a more ductile style of deformation and are more thoroughly recrystallized than the Esmond rocks on the alkalic members of the Scituate Granite Gneiss. In the Hope Valley Alaskite Gneiss, flattened and rod-shaped quartz and, to a lesser extent, feldspar impart both a foliation and a lineation. Foliation in Ten Rod Granite Gneiss is caused by planar arrangement of biotite and somewhat flattened feldspars.

Little is known about the petrology of the Hope Valley and Ten Rod rocks, but the available chemistry suggests that at least some varieties of each have alkalic affinities, whereas others are subalkaline (Figs. 3-4). As in the case of the Situate Granite Gneiss, it will be necessary to evaluate the relationships among these intermingled rocks of diverse compositions, and perhaps ages.

Zircons from our samples of these rocks are considerably discordant and yield a late Precambrian upper intercept (Fig. 7), indicating that they were emplaced during the Avalonian Orogeny. Unlike the late Precambrian Esmond Group, however, zircons from these rocks fall on a chord that has a lower intercept of 275 m.y. Additional rocks from eastern Connecticut (not reported here; R.E. Zartman, unpub. data) fall on generally similar chords and appear to reflect an Alleghenian aged event that significantly disturbed the U-Th-Pb isotopic systematics. Although the region of this disturbance is poorly constrained, the rocks most affected are either in close proximity to the Lake Char-Bloody Bluff and Honey Hill fault system in Connecticut, or in southernmost Rhode Island close to the late Paleozoic Narragansett Pier Granite pluton. We speculate that late Paleozoic deformation and magmatic activity associated with the Alleghenian Orogeny largely was responsible for the observed isotopic disturbance. Significantly, this activity has not severely affected zircon systematics from the alkalic rocks of central Rhode Island, or from the Esmond Group rocks of northern Rhode Island that fringe the western margin of the Narragansett Basin.

NARRAGANSETT PIER AND WESTERLY GRANITES: The Narragansett Pier Granite underlies much of the southern coastline of western and central Rhode Island (Fig. 1). It truncates many of the structures in the older rocks, and generally exhibits a lit-par-lit intrusive style (see Trip B-5). The rock generally is massive except for local flow foliation, and is calcalkaline in composition. The Westerly Granite is a finer-grained aplitic facies that commonly forms E-W striking dikes that dip gently to the south. These dikes, up to several tens of meters thick, especially are common in the western part of the Narragansett Pier Granite pluton near Westerly.

Rocks of this pluton cut a variety of country rocks, including Hope Valley Alaskite Gneiss, rocks of the Blackstone Series, and the Carboniferous Rhode Island Formation. Monazite, from both a white border facies and an interior pink facies from the eastern part of the pluton, have been dated by U-Pb techniques (Kocis, 1981). These data yield generally concordant ages of 276 m.y., which is compatible with the field relationships. We have dated zircon from a sample of Narragansett Pier Granite from the western part of the pluton. The zircon is mildly discordant, and yields an upper intercept of 272 ± 4 m.y., in agreement with the monazite data (Fig. 7). Generally, Westerly Granite is considered to be a comagmatic aplitic facies of the NPG. Our attempts to date zircon from Westerly Granite are not yet definitive, but suggest that it may be part of the Narragansett Pier Granite magmatic episode. Interestingly, zircon from the Westerly Granite exhibits a marked inheritance that we presently are evaluating in greater detail.

ACKNOWLEDGMENTS

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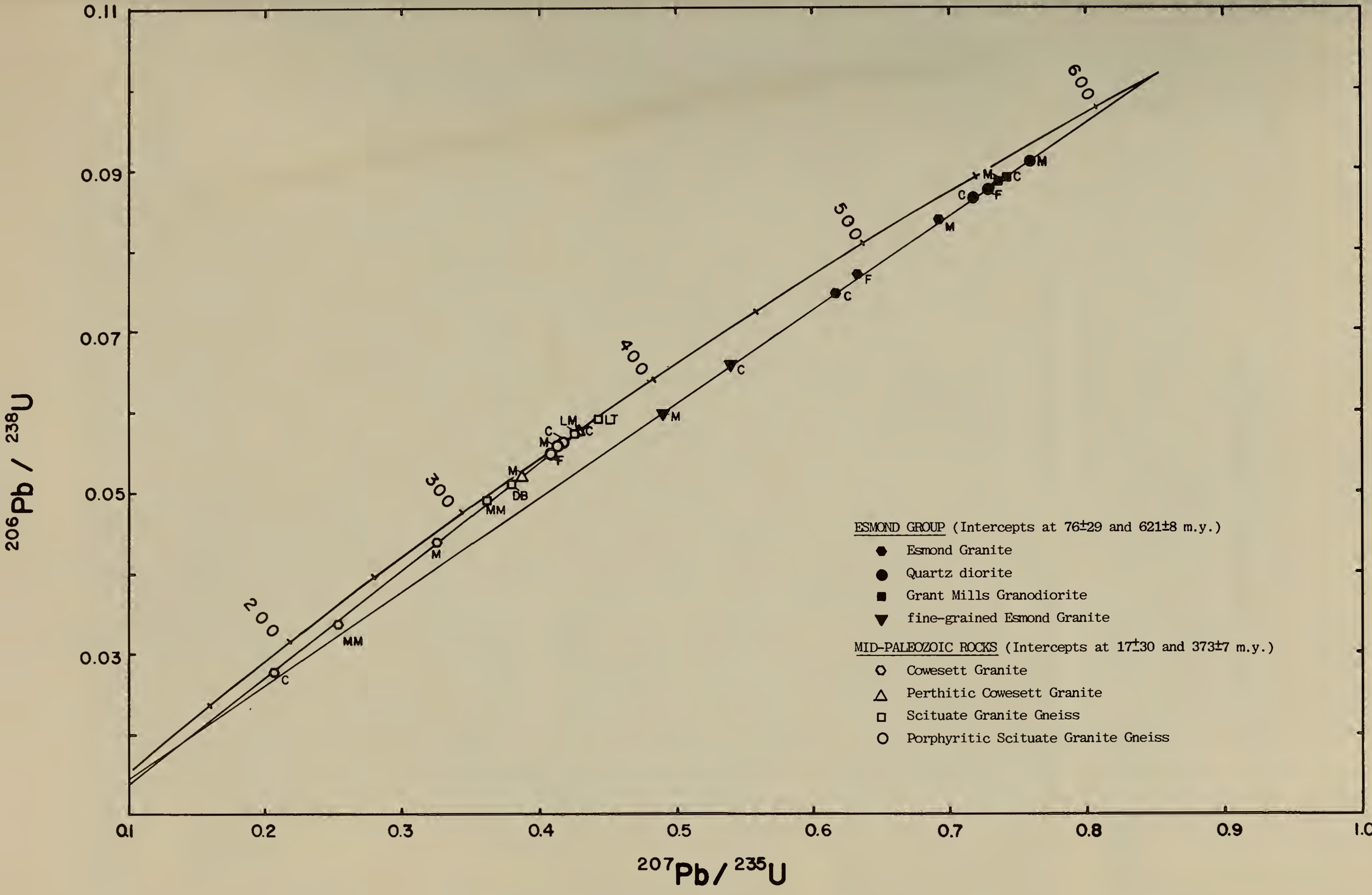

Figure 7: Concordia diagram showing distribution of: (1) zircon fractions for some Sterling Group rocks, and (2) zircon and monazite fractions from Narragansett Pier Granite. Monazite data from Kocis (1981) W = "white" facies, P = "pink" facies, other letters same as in Figure 6.

ROAD LOG AND STOP DESCRIPTION

Miles cum.	Miles int.	
0	-	Log starts at Stop 1 in Lincoln, RI. To get to Stop 1 from Kingston, travel east on Rt. 138; proceed northward on Rts. 1, 4, 2, 4, I95, and I295. From I295, take exit 9A onto Rt. 146S. Take Rt. 116W at exit, and after 0.7 mile, turn right onto Albion Road. Proceed to large outcrop behind Lincoln Mall Shopping Center.

STOP 1: ESMOND QUARTZ DIORITE (Zircon locality 8, Fig. 1)

The diorite member of the Esmond Group here intrudes schistose rocks of the Blackstone Series. In turn the diorite is cut by veins and dikes of subhorizontal to vertical aplitic granite, generally similar to the fine-grained facies of the Esmond Granite collected for zircon analysis ¼ mile to the east (zircon locality 9, Fig. 1). In addition, the diorite is cut by a compositionally composite dike that appears to be a textural variant of the host rock. The diorite is finer-grained adjacent to the Blackstone rocks at the eastern part of the outcrop, especially where lit-par-lit or webbed veinlets of diorite cut the country rock. Locally, the diorite exhibits a shear foliation, but the rock generally is more massive here than at most other outcrops. Like many other Esmond rocks, the diorite contains large anhedral quartz grains that have a distinct gray-blue hue. Plagioclase, accessory biotite, and sparse sulfides are visible in hand sample. In thin section the plagioclase appears subhedral-anhedral with thin, clear marginal overgrowths. Microcline megacrysts are sparse. Other accessories present include opaques, sphene, apatite, zircon, calcite and epidote. Partially chloritized biotite and epidote are prominent along shear fractures in this rock as well as in other members of the Esmond Group.

Within analytical error, the zircon from this diorite falls on the same U-Pb discordia as the other Esmond rocks, yielding an upper intercept of 621 ± 8 m.y. (Fig. 6). On the other hand, the three fractions of zircon from the diorite, considered alone, yield an upper intercept of 648 ± 27 m.y. This implied slightly older age is compatible with the intrusive relationship of the fine-grained granite exhibited at this outcrop as well as with the cross-cutting relationship of the Esmond Granite to be seen at Stop 2.

Retrace route on Albion Road to Rt. 116.

0.5	0.5	Turn left (east) onto Rt. 116
1.6	1.1	Bear right onto entrance ramp to Rt. 146N.
1.9	0.3	Zircons from the fine-grained Esmond Granite shown in Figure 6 (zircon locality 9, Fig. 1) were separated from a sample collected at the large roadcut to the east.

cum. int.

2.6 0.7 Bear right onto entrance ramp to I295S.

3.8 1.2 The large roadcut to the north is Esmond Granite

5.8 2.0 STOP 2: CONTACT RELATIONSHIPS OF ESMOND GRANITE AND DIORITE (Walk toward the south from the north end of the outcrop, and proceed along the Rt. 7 exit ramp).

The complexity and variety of intrusive relationships and intrusive styles which characterize the Esmond Group rocks are well displayed at this stop. In the road cut along the freeway, Esmond Granite and a dioritic rock both intrude schistose to massive mafic rocks of the Blackstone Series. In most instances the contacts between the Blackstone Series rocks and the intrusives are sharp and local stoping of angular blocks has occurred. The granite also is intrusive into the dioritic rock, but complex interfingering of these two lithologies is common. Toward the northern end of the outcrop, the granite and diorite are in fault contact. Both of these lithologies are foliated and locally highly sheared.

Additional outcrop is found by walking a short distance to the south and up the exit ramp. Here, contacts between the granite and the diorite vary from near vertical to horizontal, and from planar to lobate. Some displacement along subhorizontal, undulating planes is evident. As before, complex intermingling of the granite and diorite is common. In several areas, the diorite appears to have been incompletely solidified at the time of granite intrusion. Both lithologies are cut by felsic pegmatite dikes. Near the diorite-granite contact along the exit ramp, the granite displays a hackly fabric due to closely spaced intersecting shear joints. Mineralization is common along intersecting fracture sets and includes molybdenite and lesser pyrite, along with sericite and quartz. Locally, molybdenite platlets are sharply bent as the orientation switches from one fracture orientation to another. Mineralization is generally restricted to the granite in the contact zone near the diorite, but sparse sulfides also have been found parallel to the foliation in the diorite.

Continue south on Rt. I295.

8.9 3.1 STOP 2A: (Optional Stop) ESMOND GRANITE (Zircon locality 6, Fig. 1).

The Esmond Granite sample for zircon analysis was collected from the Rt. 44E exit ramp off I295S. Here, the granite generally is less foliated than at Stop 2, although fabric and textures are slightly variable along the extensive series of road cuts. Even where most massive, the rock contains small quantities of chlorite, epidote, and sericite in a slightly granulated texture.

Along the southbound entrance to I295, the typical Esmond Granite passes into a slightly more mafic rock with a medium- to coarse-grained seriate porphyritic texture. This rock corresponds quite cum. int. closely in lithology and texture to the Grant Mills Granodiorite whic Quinn (1971) has described elsewhere as being gradational into Esmond Granite. We will not be stopping within areas mapped as Grant Mills Granodiorite, but the characteristic features of the rock can be observed at this outcrop where it does appear to be a gradational facies of the Esmond Granite.

Several tens of meters farther south along the entrance ramp, Esmond Granite can be seen to encompass and invade masses of mafic and schistose rocks, which according to convention generally are assigned to the Blackstone Series. Mostly sharp contacts between the granite and the inclusions suggests that little reaction has occurred between them, although the granite does display more compositional variation adjacent to the inclusions compared to granite far from them. In most instances, however, no simple correlation between immediate proximity and composition is evident, and the variation include more felsic as well as more mafic compositions. Locally, however, the granite has a more mafic appearance due to the presence of small and rather well disseminated mafic inclusions.. A variety of intrusive styles are exhibited, including locally abundant angular inclusions that form an intrusive breccia. As at the previous stop, the complexity and diversity of textural and contact relationships displayed in this outcrop are the result of igneous processes.

Continue south on I295.

12.6 3.7 The large outcrops at the intersection of I295 and 195 consist of Scituate Granite Gneiss (with locally abundant xenoliths and roof pendants of Blackstone Series rocks).

13.5 0.9 STOP 3: SCITUATE GRANITE GNEISS (Zircon locality 5, Fig. 1).

This stop will allow examination of two texturally distinct lithologies which have been mapped as part of the Scituate Granite Gneiss. In the section of the outcrop that we will be visiting, the lithologies are in fault contact. In other exposures these rocks may be in intrusive contact.

To the north of the fault, the rock is a medium-grained, moderately to strongly foliated and lineated quartz-feldspar rock with usually no more than several percent biotite. Smaller quantities of minute muscovite flakes present in much of this rock are particularly evident where the rock displays closely spaced shears. The presence of some schistose inclusions indicate that this is a magmatic rock. In thin section, the only likely relict grains are scattered ragged-edged mesoperthite. The persistence of this exsolved phase suggests that the recrystallization to which this rock had been subjected was not pervasive enough to obliterate all of its primary texture.

The lithology south of the fault is a hypersolvus alkalic granite (see analysis 4, Table 1). It is distinguished from the previous lithology by its considerably coarser grain size, the common presence of sodic pyroxene, riebeckite, and tabular Carlsbad-twinned

cum. int.

mesoperthite, a much less foliated and lineated character, and a general lack of closely spaced shears. The mafic minerals are dominated by biotite which are largely grouped into thin, ovoid clots typically a centimeter or so in longest dimension. The clot-like texture, which is characteristic of type Scituate Granite Gneiss (Quinn, 1971), is recognizeable even where the rock is highly foliated. This texture stands in contrast to the finer grained and more evenly disseminated mafics in the granite gneiss north of the fault. In thin section, the rock displays mortar texture with relict igneous mesoperthite, quartz, and pyroxene-riebeckite-biotite clots set in a fine-grained matrix of quartz and feldspar. Zircon and fluorite are common accessory phases.

Zircons separated from this lithology (mildly foliated material located several tens of meters south of the fault) yield a Devonian upper intercept on concordia (Fig. 6). Although this rock is more foliated than the Cowesett Granite (Stop 4), the strong compositional, temporal, and inferred primary textural similarites between these rocks suggests that they were formed by closely related processes. The more foliated character of the lithology here, presumably, was the reason Quinn assigned it to the Scituate Granite Gneiss, but the zircon age data are in gross conflict with his field interpretations for the Scituate Granite Gneiss as a whole. As it now appears that the Scituate Granite Gneiss probably includes rocks of diverse ages and origins, a redefinition of this unit may be necessary.

The time of juxtaposition of the lithologies exposed in this outcrop is unknown, but the distinct differences in the textures and structures of these rocks suggests that the faulting postdates the development of these features. The age of the lithology north of the fault has not been determined, but there is little to suggest that it is part of the magmatic episode which generated the late Precambrian Esmond Group and related rocks. The rock here lacks the Ca-bearing phases such as non-albitic plagioclase, hornblende or epidote which are so characteristic of the late Precambrian rocks. Rather, this rock is likely to be a more recrystallized and slightly subalkaline variant (see range of chemistries for alkaline rocks, Table 1, Fig. 2-3) of the lithology south of the fault. Future work will need to address this possibility.

Continue south on I295.

16.5	3.0	Roadcut consisting of dark colored rocks of the Blackstone Series that are cut by dikes, sills, veins and pods of Esmond Granite.
18.7	2.2	Merge into southbound I95
21.9	3.2	Merge left, take exit 9 (Rt. 4S); then quickly merge right in preparation for an exit to the right.
22.4	0.5	Exit right onto Rt. 401
22.6	0.2	Continue straight through stop sign towards resturant; take sharp left and park vehicles adjacent to Narragansett Electric property. Walk

cum. int. east to Rt. 4 overpass and climb down embankment to roadcut. Walk southward along Rt. 401 exit ramp, returning to parked vehicles.

STOP 4: COWESETT GRANITE (zircon locality 4, Fig. 1).

With the exception of the relatively young Narragansett Pier Granite, the massive Cowesett Granite in this area is the least deformed plutonic rock that we have found in Rhode Island. Flow and shear foliations are absent, and the only structural features of significance are two highly sheared mafic dikes (N75W, 80N) that contain biotite and garnet and are strongly foliated parallel to the strike direction. The rock is coarse grained and contains perthitic feldspar, quartz, and irregular and sparsely dispersed mafic clots of intergrown biotite, lesser sodic pyroxene, sodic amphibole, and ragged opaques. Fluorite is common in the rock matrix as well as in localized vugs and veinlets. The colorless to milky quartz is quite distinct from the bluish quartz associated with Esmond Group rocks. The perthite is euhedral-subhedral and exhibits thin exsolution bands oblique to Carlsbad twin planes that give many grains a herringbone appearance. This texture is quite common in other alkalic plutons of SE New England (Hermes and others, 1978).

Major and trace element patterns for Cowesett Granite, as well as for the other alkalic rocks, are quite distinct from the more calcalkaline Esmond Group (Figs. 3-5). Zircon geochronology demonstrates that the Cowesett Granite is of the same age as the more foliated and deformed alkalic rocks to the north and west (e.g., stop 3 and 5). Interestingly, the Cowesett rocks are overlain unconformably to the east by younger but metamorphosed and deformed Carboniferous sediments of the Narragansett Basin. It is unclear whether this localized area somehow was shielded from the effects of the Alleghenian Orogeny, or perhaps represents an allochthons block formed in a stress-free environment.

Proceed west on Rt. 401.

22.9 0.3 Turn right (north) onto Rt. 2.

23.2 0.3 Bear right onto entrance ramp to I95S.

24.8 0.3 STOP 5: PORPHYRITIC COWESETT GRANITE

The rock exposed here was mapped by Quinn (1971) as a perthitic facies gradational into Cowesett Granite to the east. Since the Cowesett itself is a perthitic one-feldspar granite, it seems inappropriate to use this criterion to distinguish the two rocks. At this outcrop the rock is a seriate subporphyritic rock that contains perthitic feldspar phenocrysts up to 1 cm. Other nearby outcrops of this facies are more distinctly porphyritic. Generally biotite is more abundant than in the Cowesett of the previous stop. The outcrop is cut by numerous closely spaced subhorizontal shear joints that locally impart a prominent foliation. Gash veins filled with quartz cut this foliation. In thin section the margins of many feldspar and quartz grains have been granulated to form mortar texture. Accessory cum. int. minerals include zircon, fluorite, sparse pyroxene and/or amphibole, and calcite that appears secondary.

Especially prominent in the south road cut are rounded xenoliths (autoliths?) of a fine-to medium-grained igneous rock. A one meter wide diabasic dike (N25W, 80SW), that exhibits chilled margins and contains locally stopped granite fragments, cuts the outcrop on both sides of the road. This is one of the unmetamorphosed dikes that has a more alkalic chemistry and mineralogy (Pierce and Hermes, 1978) than Mesozoic dolerites associated with the Triassic-Jurassic Basins of the Appalachians (the eastern North American dolerites of Weigand and Ragland, 1970). Shear zones that cut the granite are truncated by the dike rock.

Our sample of the perthitic Cowesett facies collected for zircon dating (zircon locality 3, Fig. 1) is moderately alkalic (Figs. 3-5). Two zircon fractions lie on the same discordia chord as the Cowesett Granite which has a mid-Paleozoic upper intercept (Fig. 7).

Continue south on I95.

28.5 3.7 Take exit 6 to Rt. 3N, and turn right into unpaved commuter parking lot at end of exit ramp. On foot, cross Rt. 3 to the I295S entrance ramp.

STOP 6: BORDER ZONE OF PORPHYRITIC SCITUATE GRANITE (Zircon locality 2, Fig. 1).

The relationships observed along this road cut indicate that we are near the border zone of an intrusion, although our reconnaissance has not yet located any country rock. To best observe these features, walk along the top of the outcrop .

The northernmost part of the outcrop consists of dark gray rock that contains sparse phenocrysts of microcline in a fine-grained matrix of quartz, microcline, plagioclase, biotite, sphene, apatite, monazite, and calcite. Over a distance of 10-15 m, this apparent border facies grades into a rock which contains a greater abundance of phenocrysts and has a coarser matrix. Eventually, this facies grades into a coarse-grained porphyritic, pink rock that constitutes most of the outcrop. The pink rock contains abundant microcline phenocrysts and large strained quartz with lesser plagioclase, partly chloritized biotite, sphene, opaques, and calcite. Numerous autoliths of border facies rock occur in the pink facies, and locally the textures and lithologies are interfingered and complexly mixed (especially visible from the top of the outcrop). This mixed appearance gives the impression that the intrusion involved several pulses of emplacement.

Locally, the rock exhibits faint flow foliation of variable attitude (generally a NW strike and steep dip). Cutting this fabric are two sets of steeply dipping, closely spaced shears (N10W; N55E) that impart a deformational fabric, although locally the rock is rather massive. Several aplite and quartz veins exposed on top of the outcrop show small offsets along these shear directions.

<u>cum.</u> <u>int.</u> The textures and chemistry exhibited by the rocks at this stop are quite different from the alkalic rocks to the east (Fig. 3-5) yet zircon ages indicate that they are contemporaneous (Fig. 6). It is unclear whether this porphyritic Scituate facies represents a distinct calcalkaline magmatic episode, an allochthonous fault block, or a marginal compositional variety of the alkalic pluton. Reconnaissance examination of outcrops between stops 5 and 6 suggest that a gradational transition may exist. In future work, we intend to evaluate the hypothesis that this porphyritic facies of the Scituate Granite Gneiss exposed here might represent a more primitive calcalkaline border facies of an otherwise predominant alkalic-peralkalic pluton.

Continue south on I95.

37.8 9.3 Roadcut exposing Hope Valley Alaskite Gneiss.

38.8 1.0 <u>STOP 7</u>: HOPE VALLEY ALASKITE GNEISS

This stop is approximately one mile east of the Hope Valley Alaskite Gneiss type locality which was sampled for zircon geochronology. Here, the gneiss exhibits a lit-par-lit intrusion relationship into screens of more mafic-rich amphibole-bearing rock that may be a member of the Blackstone Series (see Fig. 11, Trip B-5). These relationships, as well as those farther to the south along I95, indicate that a least part of the Hope Valley Alaskite Gneiss truly is intrusive, and not a pile of volcaniclastics as speculated by Day and others (1980a).

The Hope Valley Alaskite exhibits a well developed foliation caused by planar arrangement of rodded and flattened quartz and feldspar. It is a two-feldspar rock of low color index with sparse biotite, opaques, muscovite, apatite, sphene, monazite, and zircon. This rock, as well as the Ten Rod Granite Gneiss of the next stop are significantly more foliated and have undergone much more ductile deformation than any of the other rocks observed at previous stops.

On a concordia diagram zircons from the Hope Valley Alaskite and Ten Rod Granite Gneisses define a chord with a late Precambrian upper intercept (Fig. 7). This upper intercept is similar to the Esmond Group rocks, and suggests that all of these rocks formed during a limited interval of time. A lower intercept of approximately 275 m.y. for the Hope Valley and Ten Rod rocks is in marked contrast, however, to the near zero age lower intercept for the Esmond Group and the Devonian-aged alkalic rocks. An important observation is that rocks containing zircons with late Paleozoic lower concordia intercepts appear to be restricted to southern Rhode Island-Connecticut, or to the region in close proximity to the Lake Char fault system of eastern Connecticut. Admittedly, this observation is based upon a limited sampling, but the rather prominent differences of textures and fabrics of Hope Valley Alaskite and Ten Rod Grnaite Gneisses, compared to the Devonian and late Precambrian rocks of central and northern Rhode Island, are rather profound. It seems reasonable to hypothesize that the Pb loss from the zircons of Ten Rod and Hope cum. int. Valley gneisses may be related to processes associated with the Alleghenian Orogeny. It has been known for some time that the K-Ar systematics of micas from much of Rhode Island and northward have undergone a rather pervasive Permian aged disturbance (Zartman and others, 1970). Likewise, ^{40}Ar/^{39}Ar release spectra from biotite and hornblende indicate that the effects of Alleghenian metamorphism extend across southwestern Rhode Island (Dallmeyer, 1981). In comparison, the area of disturbed zircons seems to be much more restricted.

continue south on I95.

39.4 0.6 Bear right at exit 3A (Rt. 138E); continue east on Rt. 138.

40.5 1.1 Park to the right along wide shoulder, across road from low outcrop.

STOP 8: TEN ROD GRANITE GNEISS

The Ten Rod Granite Gneiss contains distinctive microcline megacrysts up to 1 cm in size. Some megacrysts show crystal outlines suggesting that they may be igneous relicts, whereas others have crude augen shapes. The rock exhibits a distinct foliation (N60W, 35NE), and has layers parallel to the foliation characterized by slight differences in grain size and ratio of mafic/felsic minerals. Ten Rod Granite characteristically has a higher color index than Hope Valley Alaskite. In thin section, the Ten Rod Granite Gneiss consists of microcline, plagioclase, quartz, biotite, sphene, opaques, apatite, zircon, and monazite. The rock is completely recrystallized except possibly for some microcline phenocrysts, and owes its foliation to alignment of biotite, sphene, and flattened quartz and feldspar. The outcrop is cut by both concordant and discordant non-foliated granite and pegmatite that may be offshoots from the Narragansett Pier pluton.

Our sample of Ten Rod Granite Gneiss collected for zircon geochronology is from a locality about 15 miles east of this stop (zircon locality 11, Fig. 1); however, the texture, fabric and lithology there is quite similar. The zircon age was discussed in the previous stop description.

Make U-turn, retrace Rt. 138 westward to I95.

41.4 0.9 Enter ramp to I95S.

48.1 6.7 Take exit 1, and continue on Rt. 3S.

52.7 4.6 Turn left onto Rt. 78S

53.0 0.3 STOP 8A: (Optional Stop) RELATIONSHIPS OF NARRAGANSETT PIER AND WESTERLY GRANITES AND COUNTRY ROCK (Zircon locality 1, Fig. 1).

The road cut shows Narragansett Pier Granite intrusive into amphibolitic country rock, In turn the Narragansett Pier Granite is cut by Westerly Granite, and both granites are intruded by lamprophyric dikes that contain mantle-derived lherzolite nodules (see Fig. 13, Trip B-5). Here the pink Narragansett Pier Granite is a massive and coarse grained, equigranular two-feldspar granite. In hand sample, biotite, muscovite, pyrite, and magnetite can be recognized as prominent accessories. Sphene, monazite, allanite, apatite and zircon also are present. Westerly Granite ranges from gray to pink and contains mineralogy similar to Narragansett Pier Granite, but is a finer-grained aplitic facies.

Previous U-Pb data on monazite from Narragansett Pier Granite to the east in Narragansett yielded a concordant age of 276 m.y. (Kocis, 1981), which is in close agreement to our upper intercept zircon age of 272 ± 4 m.y. from rock at this outcrop (Fig. 7). Presently we are attempting to separate and determine a K-Ar age for phlogopite from the groundmass of the lamprophyre dike that cuts the outcrop.

END OF TRIP: To return to I95, take Rt. 78W, and follow signs to the interstate.

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THE BOSTON BAY GROUP, QUINCY, MASSACHUSETTS

by

Dabney W. Caldwell
Department of Geology, Boston University
Boston Massachusetts 02215

INTRODUCTION

For nearly a century, the origin and the age of the Boston Bay Group of sedimentary rocks has been a matter of dispute. Sayles (1914) first proposed that the Squantum "tillite" was of glacial origin and of Permo-Carboniferous age by analogy with the late Paleozoic glacial deposits of Gondwanaland. Later, Sayles (1916) described the glacial lake-environment responsible for the deposition of the rhythmically banded Cambridge Argillite. Earlier Dodge (in Mansfield, 1906) had suggested that parts of the Roxbury Conglomerate were of glacial origin.

Dott (1959, 1961) proposed that the Squantum "tillite" was a subaqueous flow or slide and represented a mixture of Roxbury gravels with Cambridge mud. Dott also proposed an earlier age for the group, perhaps Mississippian or Devonian.

In 1976, four field trips of the N.E.I.G.C. that year were concerned with the Boston Bay Group. Two trips, Wolfe (1976) and Cameron and Jeanne (1976) presented a strictly glacial origin for the rocks while the trips of Rehmer and Roy (1976) and Bailey, Newman and Genes (1976) reviewed several interpretations for them.

STRATIGRAPHY OF THE BOSTON BAY GROUP (after Billings, 1976)

			Estimated Thickness
(youngest)		Cambridge Argillite	2,000 to at least 7,600 feet
	Roxbury Conglomerate	Squantum Member	70 - 600 feet
(oldest)		Dorchester Member	about 1,000 feet
		Brookline Member	500 - 4,300 feet

Note: All units but the Squantum thicken from south to north.

COMMENTS ON THE GLACIAL ORIGIN OF THE BOSTON BAY GROUP

The comparison of the rocks of the Boston Bay Group with Pleistocence glacial deposits is not satisfactory for the following reasons:

Thickness:

As Rehmer and Roy (1976) correctly point out, a glacial lake (to contain the varve-like Cambridge Argillite) 2,000 to 7,600 feet deep is unknown in both modern and ancient environments. If it requires a fault-bounded, subsiding basin to accomplish these depths, is a glacial climate also needed to produce varve-like layers?

Lack of Abundant Sand Sized Deposits:

The most common sized particle in Pleistocene glacial stream deposits is sand, which is notably rare in the Boston Bay Group.

Lack of Obvious Deltaic Deposits:

The most common type of sedimentation associated with Wisconsin glacial lakes are deltas, a coarsening upward sequence. It is common for glacial lake deltas to prograde over glacial lake silt and clay deposits, so the sequence would go from silt and clay at the base, through sand and silt (foreset beds) to sandy pebble gravel (topset beds). The Boston Bay Group fines upward from the coarse gravels of the Brookline member to the silt-size Cambridge Argillite.

Lack of Evidence of Multiple Episodes of Glaciation:

If the rhythmically banded Cambridge Argillite is indeed a glacial lake deposit and if each layer represents a year of time, more than 200,000 years are recorded in these deposits. During this length of time there certainly should have occurred more than the single episode of glaciation represented by the Squantum formation.

FIELD TRIP

There will be only two stops on this field trip, at the Squantum Head locality, where the Cambridge Argillite overlies the Squantum member which in turn overlies the Dorchester member, and the Atlantic locality where all of the Roxbury Conglomerate units are overlain by the Squantum. At no time will we be more than a few hundred yards from our cars so that anyone can easily leave when necessary.

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Road Log

Mileage begins at Neponset Circle exit from northbound lane of southeast expressway (Route 3). If there is any interest, we can stop a few miles south on Route 128 to view the interesting contact between the Blue Hill Porphyry and Pondville Conglomerate.

Mileage (miles)	
0.0	Turn right from Route 3, to Route 3A south, move to left lane over Neponset River Bridge.
0.3	Left on Quincy Shore Drive.
0.9	Left at light onto Bay State Road.
1.1	Left on Airport Road, enter gate of U.S. Navy Housing Project and park in small lot. Stop #1. This stop will involve a walk of about ½ mile in a circular path. That will bring us back to the cars. After a walk of about 100 yards along the fence on the northeast side of project, outcrops of the Brookline member occur. Glacially (Pleistocene) polished outcrops demonstrate many properties of these rocks: obscure bedding, well rounded, clast supported pebbles. The Brookline member is exposed over about 200 feet of the twisting path. The Dorchester member is exposed over a distance of about 400 feet and consists largely of siltstone, with sandstone and conglomerate in smaller abundance. Bedding is generally obvious with occasionally convulute bedding in the siltstone. Glaciation (Pleistocene) of isolated light colored pebbles in the dark siltstone have formed large rat tail structures which my students have named ice-cream-cone structures, which they do resemble. Near the boundary with the Squantum member, large, deformed fragments of laminated siltstone are incorporated in sandstone and conglomerate which resembles the Squantum. Return to cars.
1.1	Return to Bay State Road and intersection of Quincy Shore Drive.
1.3	Turn left on Quincy Shore Drive.

1.5 Turn left at light onto Squantum Street.

2.7 Turn left onto dirt parking area near fence.

Stop #2. Squantum Head. Former site of Nike Missile Base behind fence. Walk along road to causeway leading to Long Island. Walk past gate house, cross guard rail and descend steep road band and flotsam and jetsom to Pebble Beach. Turn left (N.W.). Behind beach are outcrops of Cambridge Argillite, beds dip (are younger) toward southeast, while prominent cleavage dips steeply to northwest. At bend in shoreline, the dip slope of Cambridge beds are exposed. A few lenses of gravel are interbedded with the argillite and these increase in number and size as the Squantum member is approached.

The Squantum member is first exposed beyond a small cove but is better exposed around the bend in shoreline. Here the Squantum more resembles glacial till than in most of its outcrops. Cross over the narrow neck and turn right and just beyond wave cut notch. Here, near the base of Squantum, are beds of conglomerate and sandstone.

Turn back toward west and walk about 500 feet. The Dorchester siltstone here underlies the Squantum.

Continue along beach to path that will take us back to cars.

End of trip. Thank you.

Coastal Zone Management Problems: RI Coastal Lagoons and Barriers

by

Virginia Lee and Jon C. Boothroyd
University of Rhode Island

INTRODUCTION

The barrier spit-lagoon complexes that stretch along the south shore of Rhode Island are among the state's most valued natural resources (Figure 1). The area has the most rapidly growing year round residential population in the state and every summer, thousands of tourists come from all over the region to fish, boat, and bath on these shores. Their relatively-shallow depth and isolation from major cities have for the most part not made them attractive for intense commercial development. There is a long history of attempts to manage the lagoons and beaches to enhance their fisheries production and tourist appeal. As relatively small coastal systems with restricted exchange with offshore waters, they are particularly susceptible to the impacts of even residential and light commercial development on the shoreline and in the entire watershed. This field trip is designed to explore some of the ways in which the geology of the lagoons and barrier spits constrains patterns of development and options for coastal zone management.

For instance, most of the south shore lagoons, known locally as salt ponds, had permanent breachways constructed in the 1950s in order to enhance productive oyster fisheries, increase flushing, and improve access to the sea for recreational boating. The breachways are major controls of the ecology of the ponds since they regulate exchange with the ocean, which alters the nutrients and salinity, the flushing, the sedimentation rate on the flood tidal delta and access to the sea for migrating fish. These parameters are basic ingredients controlling the kinds of life that flourish in the ponds. We know from the past that changes in the size, duration and location of the breachways dramatically affected the ecology of the ponds. We also know that attempts to alter the breachways to better manage the ponds, have had far-reaching and often unforeseen consequences. Ironically, the stabilization of the breachways increased the flushing and salinity in the ponds enough to cause the demise of the very fisheries they were meant to enhance. As permanent connections to the sea, they accelerated the rate of sedimentation on the flood tidal delta building shoals that restricted, even proved harzardous to recreational boating.

CHARLESTOWN BREACHWAY

The Charlestown Breachway (stop 1) is a prime example of the problems inherent in attempts to manage complicated ecosystems. Before it was reinforced, the breachway would open and close several times a year in response to storm overwash and longshore drift. The opening and closing of the breach resulted in a pulsed salinity, conservative circulation, brackish environment in the ponds that was exceedingly productive. Indian shell middens on Fort Neck and Foster's Cove indicate that the ponds have produced abundant oysters for at least 1000 years.

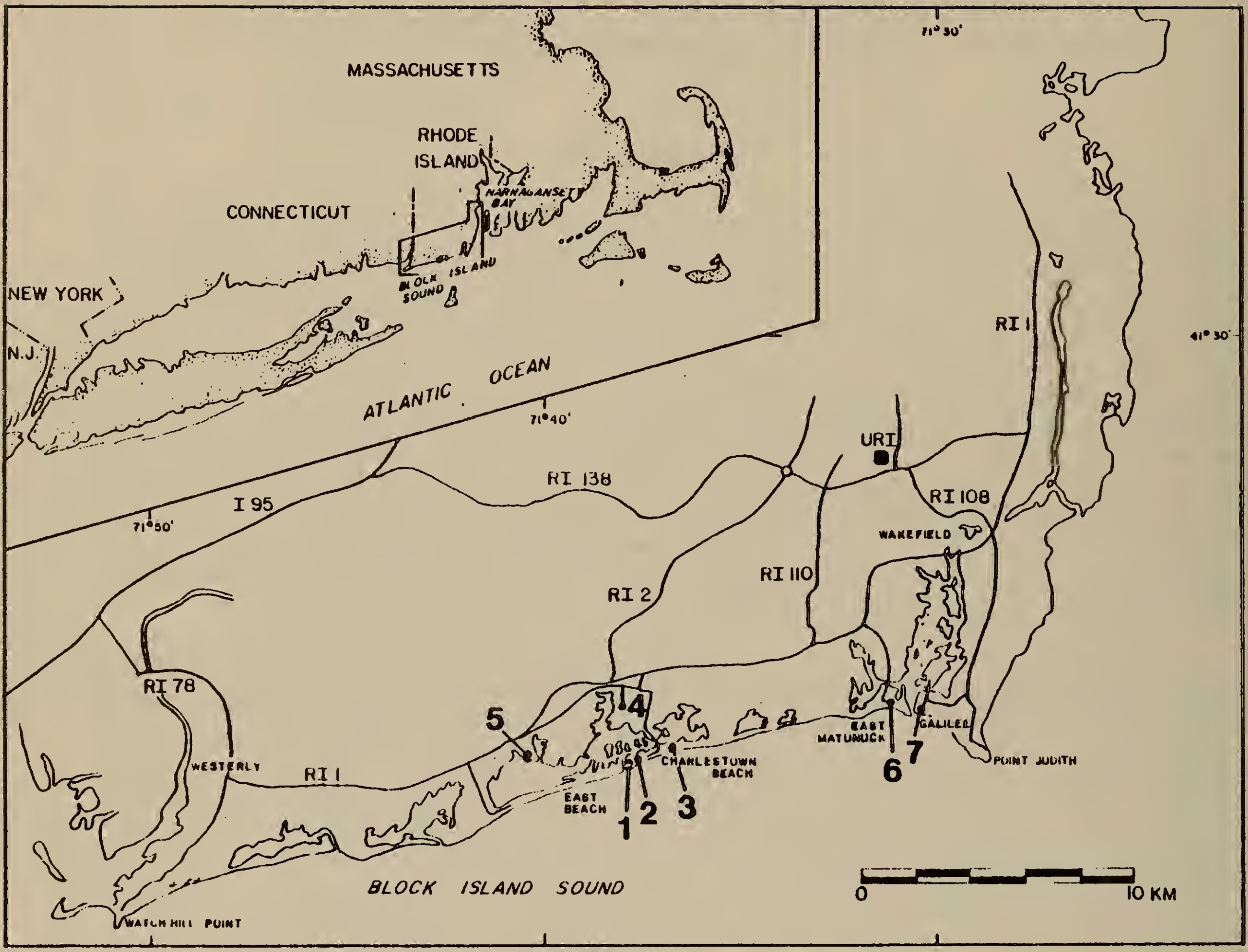


Figure 1. Rhode Island's south shore barrier spits and lagoons, which stretch from Watch Hill east to Point Judith. Field trip stops are enumerated on the map.

Reports from early fisherman indicate that they also supported extremely abundant finfish yields as well. Thousands of pounds of oysters, perch, and alewives were fished from these ponds in the 1800s and early 1900s.

Attempts to reinforce the breachway to make a permanent connection to the sea started at least 100 years ago. In the late 1800s, when Narragansett Bay supported an enormous oyster fishery, the state looked to Charlestown and Green Hill Ponds as a steady source of oyster seed to be transplanted to the commercial beds in the Bay. Even though the oysters spawned produgiously in the ponds, it was thought that the set would grow better if the ponds were flushed with more seawater. So in 1881, the state paid for the Charlestown breachway to be reinforced with a rock wall on the west side and leased out sections of the pond for oyster culture (Figure 2).

For decades afterwards, the breachway shoaled in every year as longshore currents sealed off the entrance. Every other year the state would have it dredged out. In 1952, the permanent breachway was constructed, reinforced with granite riprap and dredged to its present configuration of 2 meter depth and 34 meter width.

However, the opening of the permanent breachway eventually caused the loss of the uses of the pond that it was meant to enhance. Oysters that once covered the sand flats along the back of the barrier and were harvested by the hundreds of bushels, can only be found in coves where fresh water comes into the ponds via springs or streams. The abundant brackish water finfisheries no longer exist. Sand eroded from the barrier beach is carried in through the breachway and deposited on a flood tide delta that is rapidly shoaling inside the pond (Figure 3). Boaters and fishermen can no longer easily navigate the channels that wind through the sand flats and out through the breachway. Fishermen and local residents fear that accumulating sediments are blocking adequate flushing of both Charlestown and Green Hill Ponds. If flushing becomes too reduced, the ponds or back coves will stagnate and choke with algae leading to the eventual death of fish and shellfish due to low oxygen. Some local residents are alarmed that east basin will soon be filled in and they will be living on sand flats instead of a pond. Local residents are demanding that something be done about the breachway to stop the ponds from shoaling, to insure that the excellent water quality is retained and that the fin and shellfish resources continue to be healthy and productive.

Jon Boothroyd (1981) has researched the processes of erosion and sedimentation in Ninigret Pond. The data will be used to help the state agencies decide how to make sound management decisions regarding breachway manipulation and dredging in the pond. The geological research and the constraints of geological processes on the various options available to the state will be discussed at the site.

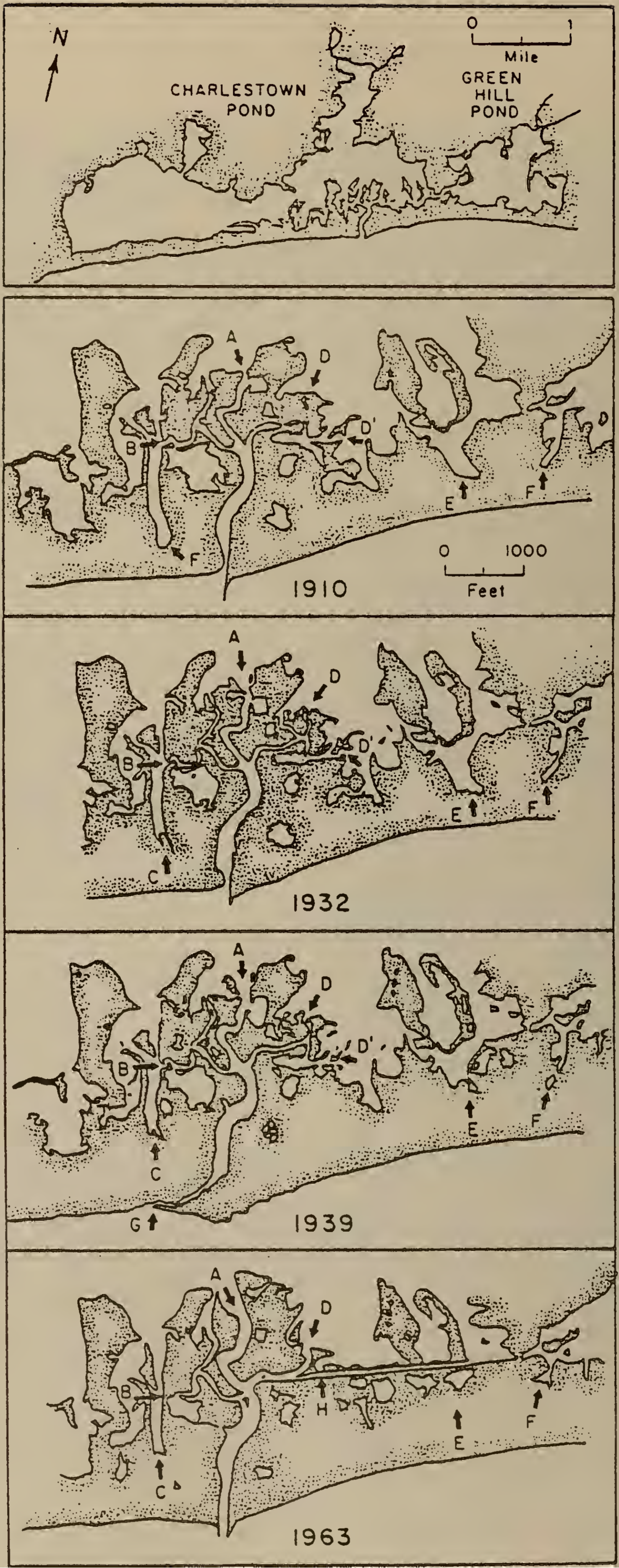


Figure 2.

Maps of Charlestown and Green Hill ponds showing changes in the breachway and major tidal delta channels over time.

Figure 3. Photograph of the Ninigret Pond flood tidal delta and adjacent barrier spits. Photo taken June 28, 1981 by Jon Boothroyd.

GREEN HILL AND CHARLESTOWN EAST BEACH

The Green Hill and Charlestown East Beach (Stop 2 and 3) is a developed barrier spit beset by a host of difficult management problems. It is an eroding beach and an active overwash area. It is an east-west oriented beach with a prevailing southwest breeze and ocean waves which make the beach and any development particularly susceptible to storm damage not only of hurricane magnitude but even in more common storm events. Beach and dune erosion occur during southeasterly winter storms, and during late summer and fall hurricanes. Measurements using time series aerial photographs indicate that the south shore barrier beaches and foredune ridge are eroding at an average rate of 0.2 m yr^{-1} (Regan 1976). Fisher and Simpson (1980) determined that some areas are eroding more rapidly than others, and give the accelerated rate of 0.7 m yr^{-1} for those localities.

Twenty-four hurricanes have caused coastal erosion and flooding during the past 165 years (1815-1980). Two very large hurricanes in 1938 and 1954 (Carol) resulted in huge hurricane surges, 4.4 m and 3.0 m above mean high water respectively (Olsen and Grant, 1973).

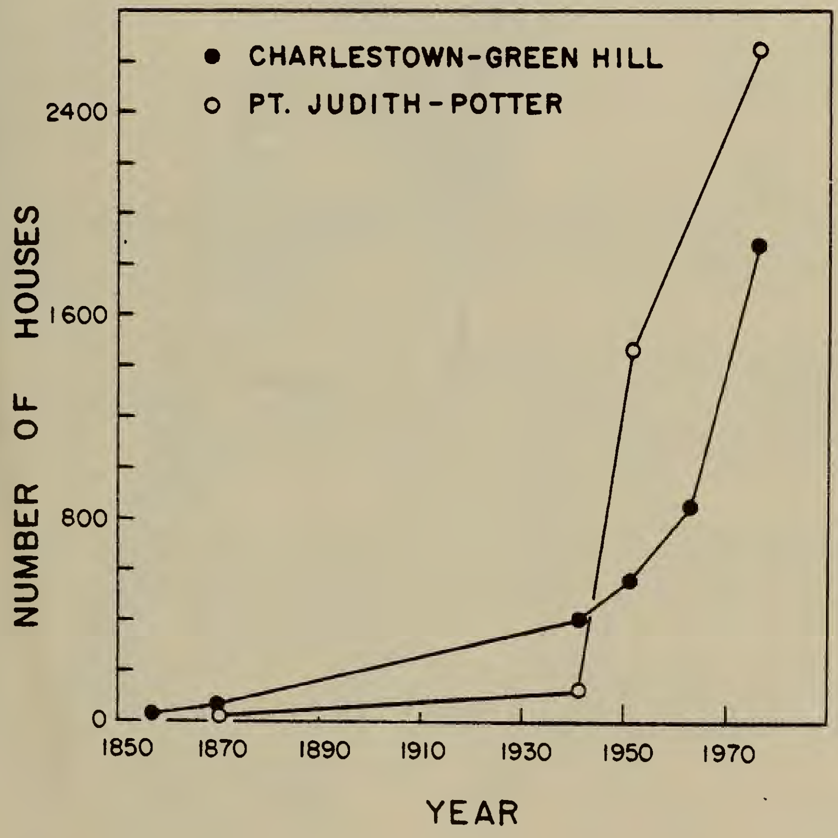
The storm surge from these hurricanes washed huge volumes of sand over the barriers and swept houses, roads, automobiles, and people over the barrier and across the ponds onto the far shore. There have been numerous winter storms that have also caused severe erosion of the beach and overwash into these ponds. The blizzard that stalled New England in the winter of 1978 also did considerable damage to the houses on Charlestown East beach. Two houses were lost, several were severely damaged.

As a result of the extensive flooding and millions of dollars of destruction caused by the hurricanes of 1938 and 1954, coastal Rhode Island towns bought into the federal flood insurance program. The flood insurance program has subsidized development of barriers where local banks would not. The ways in which the floo insurance program has exacerbated problems of barrier beach management will be discussed with pertinent examples demonstrated at stops 2 and 3.

LIMITATIONS OF OUTWASH SOILS TO DEVELOPMENT

The Fosters Cove development (stop 5) is an excellent example of the constraints that the glacial outwash soil around the ponds put on residential development. After World War II, the standard of living improved enough for people to be able to afford summer houses on the south shore. Most of these houses had cesspools or piped waste directly into the ponds. Since housing was only seasonal, there was little noticeable pollution of the ponds. However, sinc the highways were improved in the 1950's putting the south shore in easy communit distance to industiral centers, the south shore has accomodated dramatic increase in residential development (Figure 4). Virtually all of the houses within the watershed have septic systems and private wells. Public sewers and town water have only recently been installed around Point Judith Pond. Since the direction of flow is toward the ponds (Figure 5) and the percolation rates are very high in the glacial outwash plain, septic seepage is contaminating groundwater and the ponds. During the summer months, coliform levels in Green Hill, Trustom, Cards and upper Point Judith ponds are above recreational fishing standards. These ponds are important recreational fishing areas.

Furthermore, the additional nutrient loading is contaminating drinking wells and probably accelerating eutrophication of the ponds. In contrast to fresh water systems where phosphorus is the limiting nutrient in coastal waters, nitrogen is limiting. Most of the nitrogen in septic sewage is oxidized to nitrate in the groundwater around the ponds. Since nitrate does not bind to soil particles especially coarse outwash soils, it travels with the groundwater to the ponds. These issues will be discussed in relation to Fosters Cove where a proposed residential development has the potential for particularly negative impacts on the coastal zone. The cove is one of the last good oyster spawning areas in the state. Due to the narrow construction where it connects to Ninigret Pond, flushing is reduced and it is particularly susceptible to the ills of eutrophication due to increased nutrient loadings from surrounding development.



gure 4. A graph of the dramatic increase in residential development in the outwash plain surrounding the ponds. Particularly rapid growth has accrued since the 1950s.

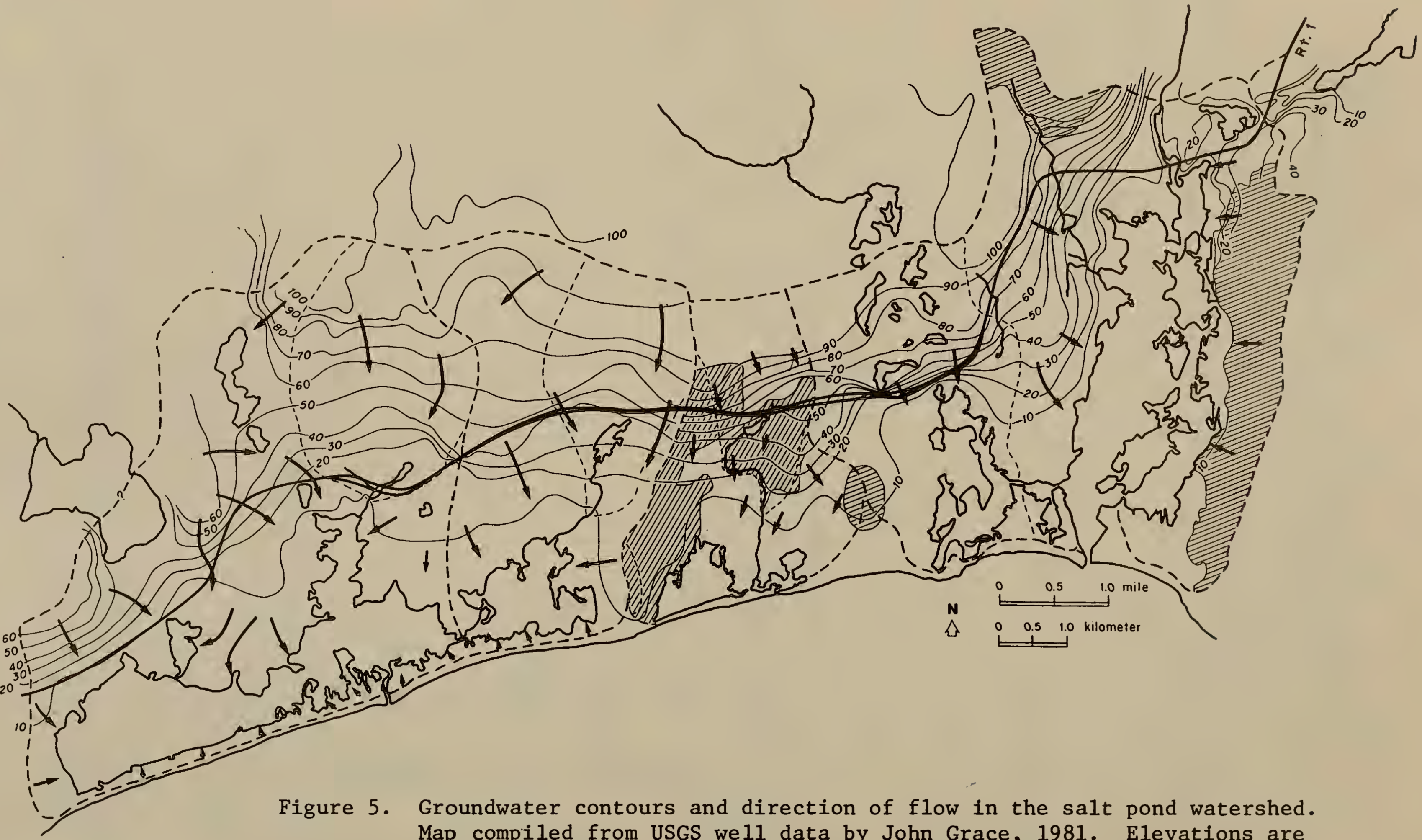


Figure 5. Groundwater contours and direction of flow in the salt pond watershed. Map compiled from USGS well data by John Grace, 1981. Elevations are in feet above mean sea level. The crosshatching represents glacial fill in what is otherwise glacial outwash and morrain deposits.

LARGE SCALE RECREATIONAL BEACH FACILITIES

The state bathing pavilion at East Matunuck beach (stop 5) is an instructive contrast to the bathing pavilion at Sand Hill Cove (stop 6). At East Matunuck, the location of the parking lot exacerbates the overwash process, shunting sand and gravel over the barrier and filling Succatash Marsh, a state wildlife sanctuary. The pavilion is built high on an unprotected coast where hurricane surges have already washed over the barrier and into Potter and Point Judith Ponds. The beach is eroding relatively rapidly making it susceptible to future storm events in contrast to Sand Hill Cove beach, which is in the lee of the protective breakwaters of the Harbor of Refuge. The management problems inherent in the recreational structures will be discussed. The development of the Port of Galilee and harbor dredging and spoil disposal practices will also be explored.

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Itinerary

The field trip will leave from the Keaney parking lot beside the athletic fields, University of Rhode Island. It involves walking on beaches and dunes. Sneakers or tennis shoes are recommended.

Distance (In Miles)		Routes and Stops
Tot.	Cum.	
0	0	Leave Keaney parking lot, turn right (west) on RI 138.
0.6	0.6	Intersection of RI 110 at lights. Turn left (south) on RI 110. This route, also called Ministerial Road.
3.8	4.4	Tuckertown Four Corners, intersection of Wordens Pond Road on the right (west), and Tuckertown Road on the left (east). Located on ice-contact deposits just north of the Charlestown end moraine. Proceed south through the intersection and up onto the moraine.
0.7	5.1	Backside (ice-contact slope) of Charlestown moraine.
1.3	6.4	Intersection with Old Post Road, and beginning of proximal outwash plain. Proceed south to US 1.
0.2	6.6	US 1, go west past exits to Moonstone and Green Hill beaches. Charlestown moraine on the right.
1.2	7.8	Charlestown Beach exit: exit from left lane onto US 1, north.
0.3	8.1	Exit right at Charlestown Beach breachway sign. Proceed 100 yards to stop sign (intersection with US 1A); continue straight through stop sign. Passing over proximal outwash plain (former potato farms).
0.5	8.6	Turn left at Stop sign onto Schoolhouse Road; follow Beach/Breachway signs.
0.1	8.7	Turn right onto Charlestown Beach Road. Proceed south on the outwash plain; across a small till upland, and down to the lagoon.
1.3	10.0	Green Hill Pond bridge: Charlestown Pond with dredged channel to the right; Green Hill Pond to the left (small island with house is a till upland). Beyond the pond is Green Hill, a drumlin.
		Bear left off bridge onto back barrier. Proceed 200 yards.
0.2	10.2	Bear right to travel west along the back barrier. Example of a developed barrier spit, most structures built since 1970.
0.5	10.7	Location of CHA-EZ profile.

0.1	10.8	Two houses on left lost in 1977-78; passing area of active overwash.
0.1	10.9	Charlestown Breachway (State Camping Area gravel parking lot).
		STOP 1. Charlestown Breachway.
		Leave breachway parking lot, heading east along back barrier.
0.2	11.1	Location of CHA-EZ beach profile.
		STOP 2. Charlestown Beach.
		Return east along the back barrier.
0.5	11.6	At the junction of Charlestown Beach turn right, proceed 100 feet toward the ocean, make a sharp left and continue east along the barrier spit.
0.5	12.1	STOP 3. Green Hill Beach.
		Walk to pole No. 8850.
0.7	12.8	Return west along the barrier turning right onto Charlestown Beach Road to the Green Hill Pond Bridge. Drive north along Charlestown Beach Road.
1.3	14.1	Intersection Charlestown Beach Road and Schoolhouse Road. Turn left at stop sign on Schoolhouse Road.
		On your left housing developments are being built on proximal outwash plain, where the eolian mantle is Bridgehampton silt-loam, some of the finest agricultural soil in the state.
0.4	14.5	Intersection of Schoolhouse Road and US 1A. Bear left along US 1A south. WATCH CLOSELY FOR NEXT TURN.
0.1	14.6	Turn left private gravel road, follow it till it ends in a borrow pit.
0.2	14.8	STOP 4. Outwash Gravel.
0.2	15.0	Return out the gravel road to Rt. 1A. Turn left (west) US 1A.
0.5	15.5	Cross Mills Village. A water driven grist mill operated here in the 1700's grinding corn grown on the local coastal farms where the outwash soils were fertile, relatively rock free, and the climate mild compared to farms north of the moraine. We also pass the entrance to Fort Ninigret, a major summer encampment and trading post for the Niantic Indians. Artifacts indicate that it was a center for trade with other tribes and with the Dutch in colonial times.
0.6	16.1	Intersections of US 1A and US 1. Proceed east 300 yards and exit left across the median strip (Proceed west on US 1).
0.7	16.8	On your left is an abandoned Charlestown Air Station developed to train night fliers during WW II. It was a proposed site for a nuclear generating station.

0.7	17.5	On your left is Foster's Cove and Charlestown Pond. On a clear day Block Island can be seen on the horizon.
0.4	17.9	Exit left across median at the Hitching Post hot dog stand and proceed south across outwash plain to the pond (private road).
0.5	18.4	Bearing left, stop at the grey house with a sign saying "Seeley": (2nd house on right).
		<u>STOP 5</u>. Foster's Cove.
		Return to US 1.
0.6	19.0	Turn right on US 1 heading east. Drive east several miles along the Charlestown moraine.
8.4	27.4	On your right is Perch Cove, a kettle hole connected to the north end of Potter Pond.
0.7	28.1	Exit right off US 1 at East Matunuck State Beach, Jerusalem, Snug Harbor sign. Head south on Succotash Road, traveling over ablation moraine and kame terrace.
0.7	28.8	Potter Pond bridge. Point Judith Pond is on the left connected under the bridge to Potter Pond on your right. The salt marsh south of the bridge is growing on a relic flood tidal delta. The houses on the right are built on fill and glacial islands.
0.6	29.4	Bear right into the East Matunuck State Beach. Park in the State Beach parking lot next to the beach pavilion.
		<u>STOP 6</u>. East Matunuck.
		Return north along Succotash Road; over Potter Pond bridge to US 1.
1.9	31.3	Bear right onto US 1 heading east. The marinas on your right are on upper Point Judith Pond.
3.8	35.1	Exit right off US 1 at sign for Point Judith, Scarborough, and Galilee. Proceed up off-ramp; turn right onto Woodruff Avenue; follow signs for Point Judith. Bear right at lights onto RI 108 (south). Drive south on RI 108 several miles, through to intersection with traffic lights. You are traversing along Point Judith end moraine.
4.2	39.3	Fisherman's Memorial State Park on right: the site of coastal defense gun batteries guarding the east entrance to Narragansett Bay during WW II.
0.1	39.4	Exit right off RI 108 onto the Escape Road. So many lives were lost at Galilee during the hurricane of 1938 that the road was built as a hurricane escape route. Ironically, only the gravel foundation fill was in place in 1954 when Hurricane Carol washed all gravel onto the tidal flats on the north side of the road.

1.2 40.6 Turn left (south) at T-intersection. This is the village of Galilee, the major commercial fishing port in the state and the terminal for the Block Island ferry.

0.4 41.0 Turn right into the parking lot at the breachway.

STOP 7. Point Judith Breachway.

END OF TRIP

INTERPRETATION OF PRIMARY SEDIMENTARY STRUCTURES

Jon C. Boothroyd[1]

INTRODUCTION

The purpose of this trip is to investigate the nature and origin of stratification and cross-stratification in glacial sediments and in beaches (Fig. 1). The principles and interpretations are not new, indeed most have been well established in the literature for 5-10 years, and reported much earlier than that. What I have observed in 16 years of field work however, is that the patience and care needed to extract information on sedimentary structures from unconsolidated exposures is often lacking. The purpose of the trip is to demonstrate some techniques for preparing exposures and interpreting the results.

The techniques and equipment are absurdly simple: 1) long-handled, pointed shovels for the beach, together with a scraper to smooth the trench walls. I use an aluminum, custom-made trowel (a "magic scraper") first developed by Miles Hayes and myself at the University of Massachusetts. You MUST USE some kind of smoothing device to bring out the details of the stratification. For working in borrow pits in glacial sediments, swap the long-handled shovel for an entrenching tool (foxhole shovel). Use it with the blade locked at a 90° angle to the handle to rough finish pit faces, then fine tune with a scraper. The magic scraper does not work well in fine-grained silt and clay, so a variety of smaller trowels, filet knives, and spoke shaves have been employed. Lastly, use a proper scale for your pictures; one that is clearly graduated and easy to see. Lens caps, pencils and your foot are decidedly second best, and very few Recent and glacial sedimentologists carry a hammer.

REVIEW OF BEDFORMS AND CROSS-STRATIFICATION

This quick review will serve to set the stage for the sedimentary structures you will see on this trip. Please refer to Harms et al. (1975), Walker (1979), or Blatt et al. (1980) for excellent discussions in detail.

Bedform morphology changes with increase in flow strength from straight-crested bedforms, often called 2D, to highly irregular cuspate, or lunate shaped crests (3D) (Fig. 2). As flow strength further increases, the bed is planed to a flat-bed configuration. Many different bedform classification schemes have been proposed based on increasing flow strength; Simons and Richardson's (Fig. 3B) is perhaps the best known. Figure 3A lists the scheme in general use by the Coastal Research Division at the University of South Carolina, and by our group at Rhode Island.

The sedimentary structures or stratification produced by the slipface migration

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[1] Department of Geology, University of Rhode Island, Kingston, RI 02881

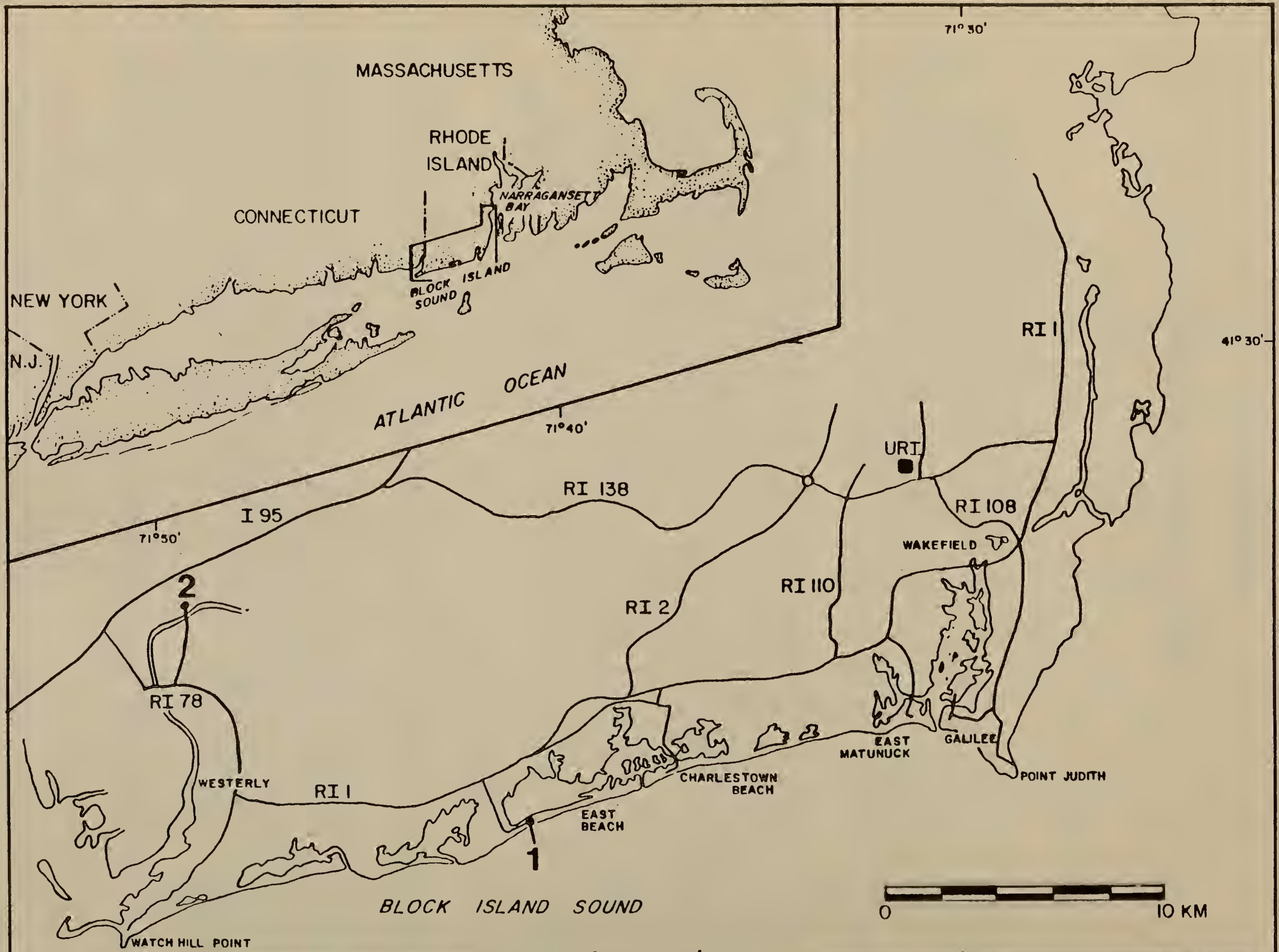


FIGURE 1. Location map.

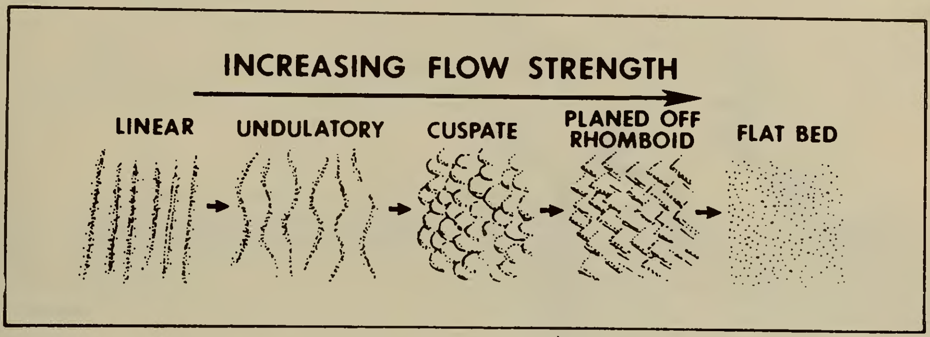


FIGURE 2. Change of bed morphology with increasing flow strength (from Hayes and Kana, 1976).

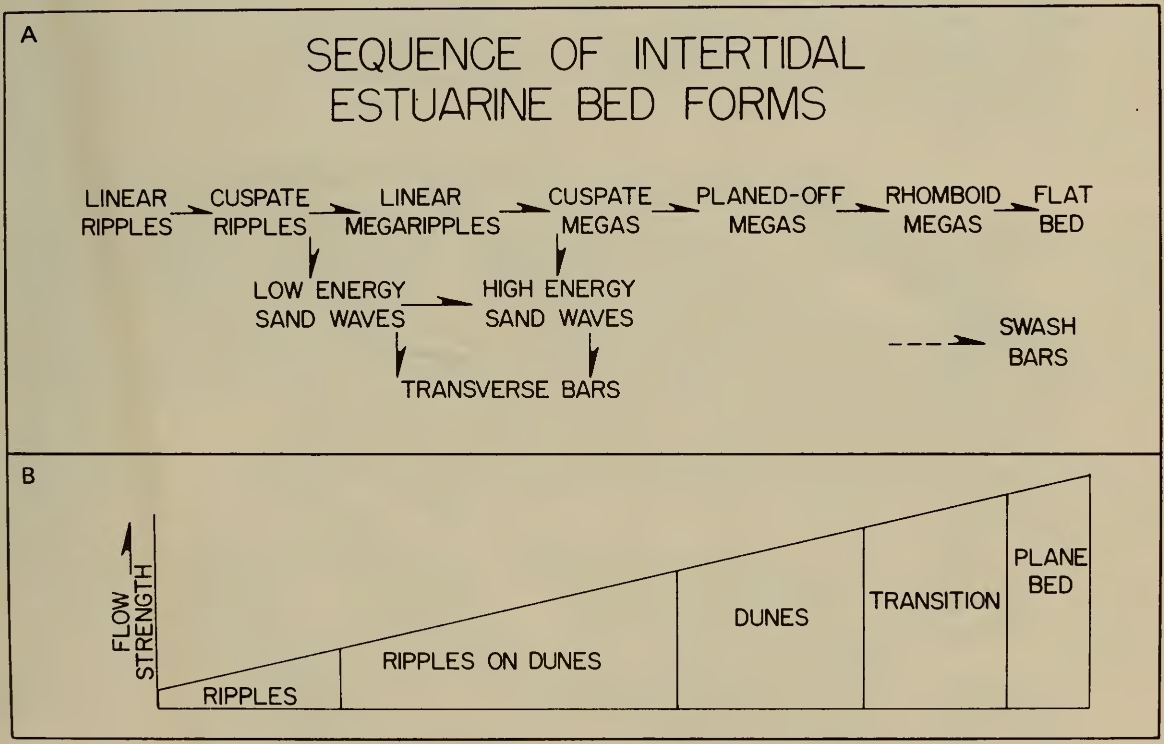
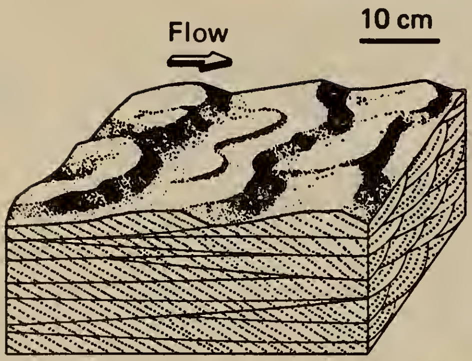
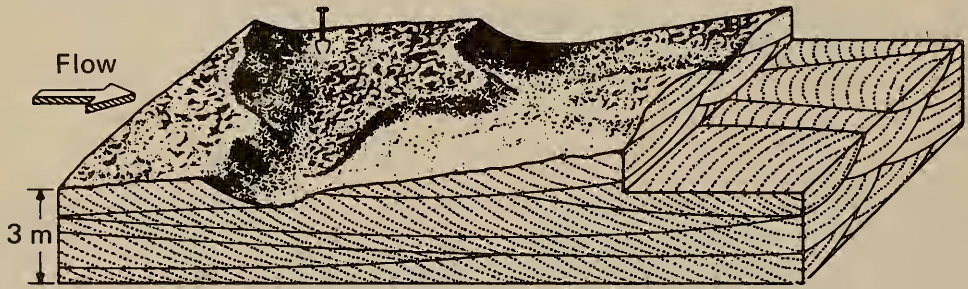


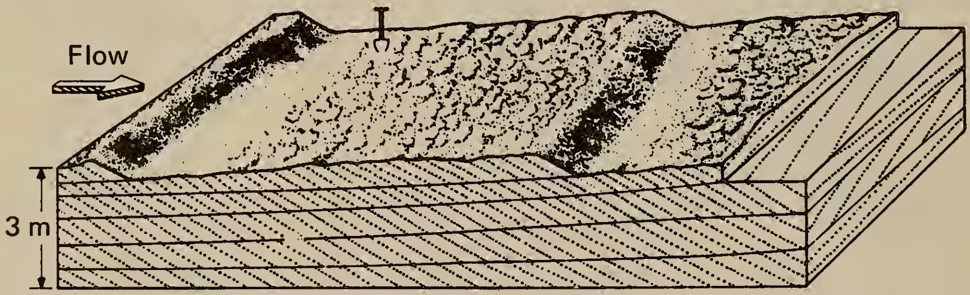
FIGURE 3. Bedform classification schemes (Boothroyd, 1978).
A. System developed for mesotidal estuaries.
B. Simons and Richardson's (1961) classification.



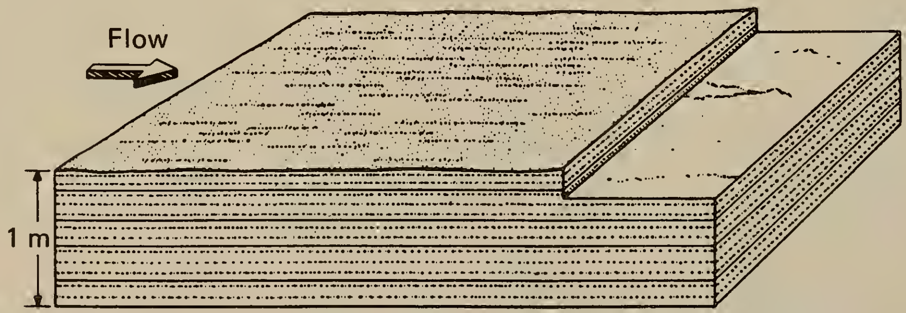
A. Small-scale trough cross-stratification produced by migrating cuspate ripples.



B. Large-scale trough cross-stratification produced by migrating cuspate megaripples.



C. Large-scale tabular cross-stratification produced by migrating linear sand waves.



D. Horizontal stratification produced by upper flat bed deposition with current lineation. Internal surfaces show parting lineation.

FIGURE 4. Stratification types produced by the migration of various bedforms and bed configurations (modified from Harms et al., 1975).

of bedforms (and by flat bed configuration) are illustrated in Figure 4. The morphology of the bedform exerts a strong influence on the form of the internal cross-stratification and the nature of the bounding surfaces. Cross-stratification type can be linked to bedform scale and morphology, and bedforms can be tied to the strength of flow generating the bedform. Thus we can examine sedimentary structures and say something about the energy of the depositing current.

EAST BEACH

East Beach, Stop 1, is a low, narrow, microtidal barrier spit, 5.0 km long, connected to the mainland at Quonochontaug Neck and extending eastward to the Charlestown breachway (Fig. 1,5). The beach exhibits a mature depositional profile consisting of a high flat berm and a steeply dipping beach face (Fig. 6A). The recovery profile after storms is an example of a classic ridge and runnel (Fig. 6B). The ridge, or swash bar, quickly welds to the incipient berm several days after the storm passes. See trip B-9 for more details on the coastal geology of the Rhode Island south shore.

Beach Stratification - Most stratification found in beaches is formed by the dual process of swash uprush and backwash on the beach face and on the berm top. Flow is under upper-flow regime, flat-bed conditions that deposits plane lamination. The pulsating nature of the wave-generated swash gives rise to a series of sets of plane lamination separated by very low-angle truncations as depicted in Figure 7A. Important features to note are: 1) general seaward dip of the lamination; 2) the low-angle truncations between the sets; and 3) the erosional nature of the set contacts. Laminae deposited on the beach face dip seaward at angles of 2-10°, but laminae deposited on the berm top may be horizontal, or dip slightly landward (1-2°). Figure 8A illustrates beach face and berm top stratification; note the prominent truncation indicating an erosional event.

Another type of stratification found in beaches is tabular cross-stratification dipping in a landward direction (Fig. 8B). It is formed by the migration of slipfaces of swash bars (ridges) across the low-tide terrace. This process and type of stratification was first described in detail by Hayes (1969). The swash bars weld rapidly on the Rhode Island south shore and the tabular cross-stratification is usually overlain by over a meter of beach face and berm top plane lamination.

A third type of stratification, hummocky cross-stratification, has not been documented in beaches, but may indeed exist (Fig. 7B). Hummocky cross-stratification (Harms et al., 1975) has been described in various rock sequences (Walker, 1979; Harms et al., 1965; Howard, 1972) but not yet described in Recent sediments. It is thought to form on the shoreface under storm-wave conditions that induce unidirectional surges. However, these conditions are duplicated on erosional low-tide terraces, so "hummocky" or H.C.S. may exist on beaches. Look closely.

BOOM BRIDGE BORROW PIT

The borrow pit is located just over the Pawcatuck River in Connecticut, in the Ashaway 7½ minute quadrangle. Schafer (1968) mapped the area as glacial stream and lake deposits of the Chapman Pond - Green Fall River sequence. Sedimentation occurred during late Wisconsinan deglaciation as a series of small deltas built into ponds and small lakes that were totally filled and then capped by fluvial gravel. The ponds were adjacent to, and partially formed in, stagnant ice that

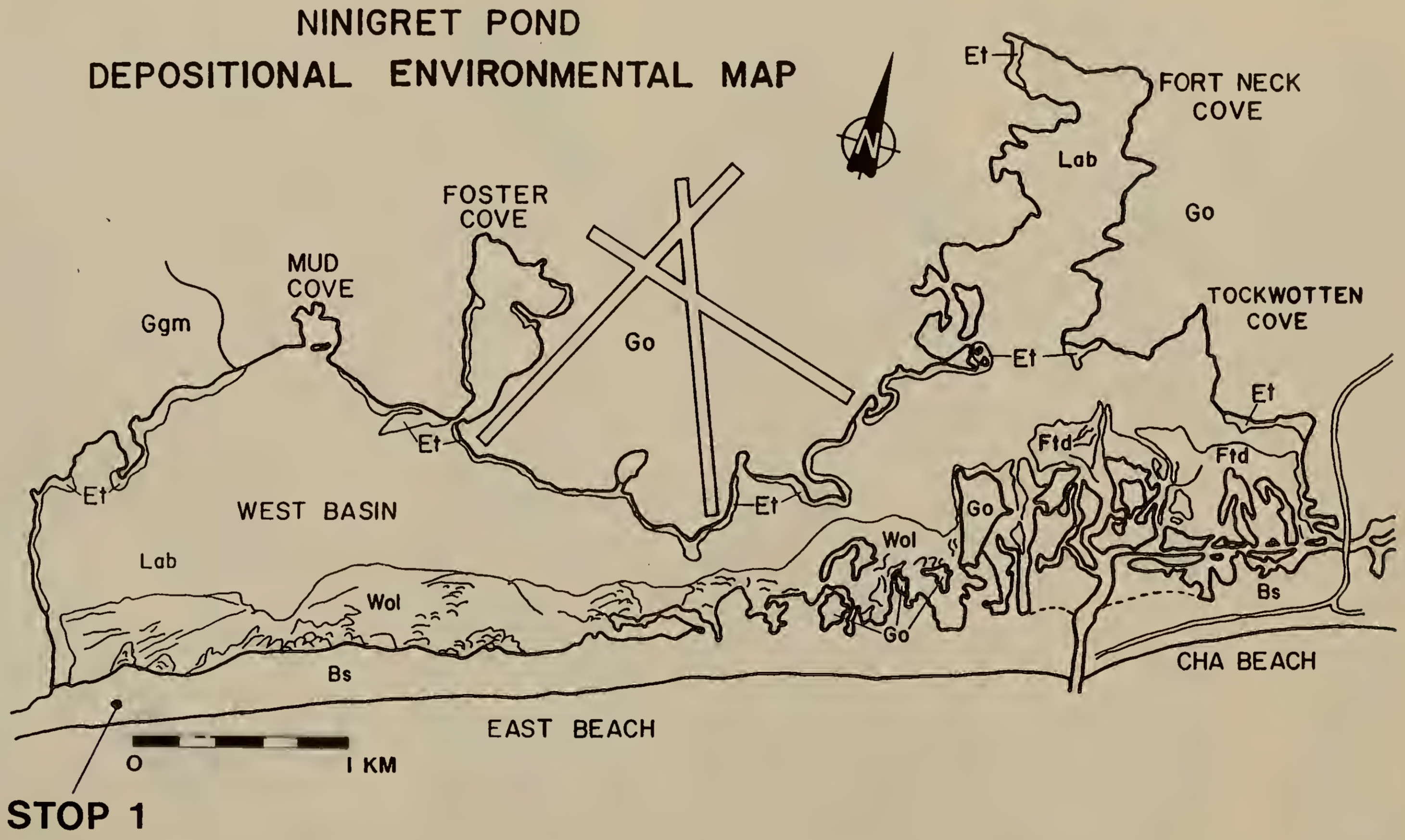


FIGURE 5. Simplified depositional environmental map of the East Beach, Ninigret Pond area. Bs: barrier spit; Wol: washover platform; Ftd: flood-tidal delta; Lab: low-energy lagoon; Et: erosional terrace; Go: glacial outwash; Ggm: ground moraine

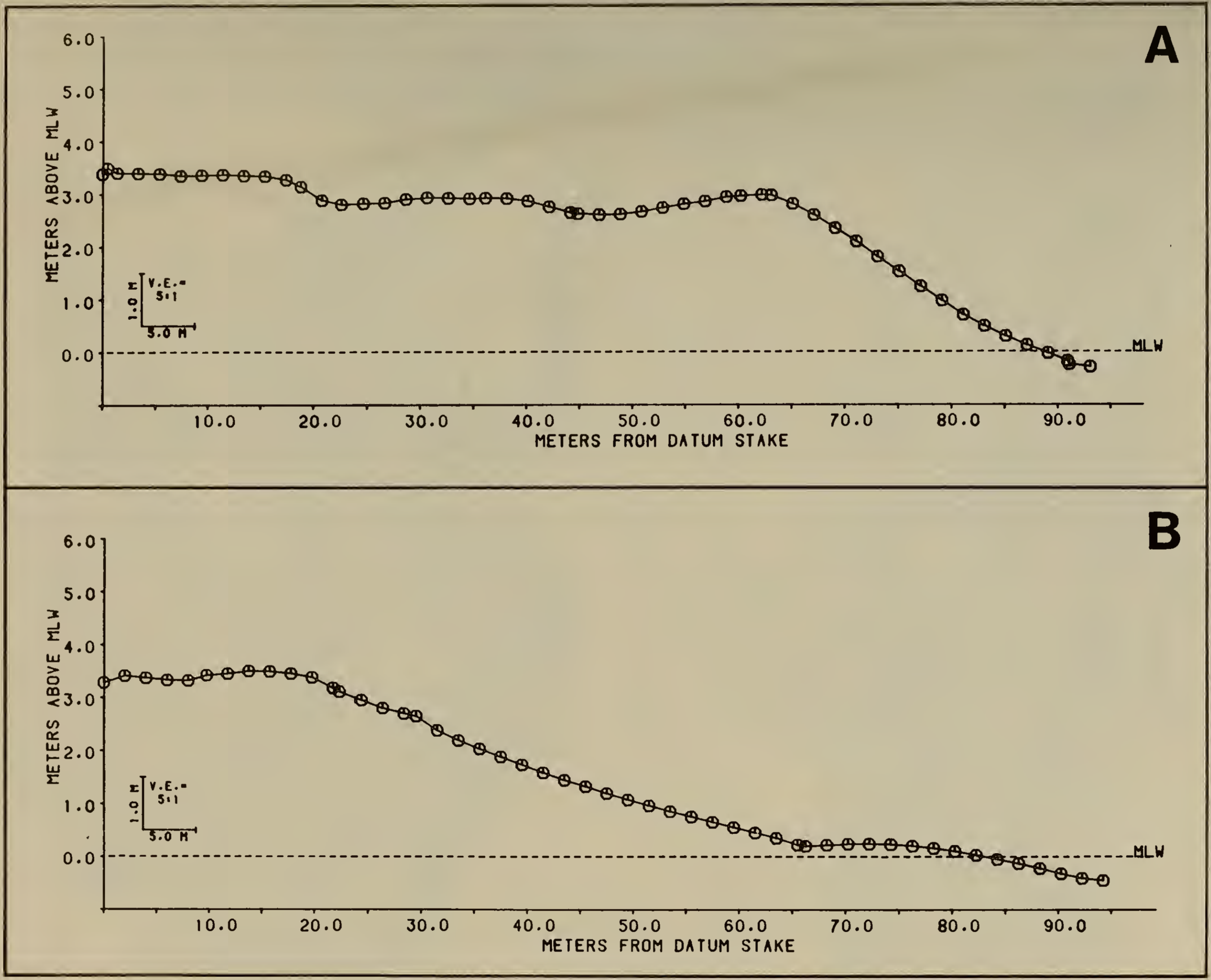


FIGURE 6. Typical profiles of beaches on the Rhode Island south shore.
A. High depositional profile, late summer 1979.
B. Erosional storm profile, October 1980. Note the small swash bar.

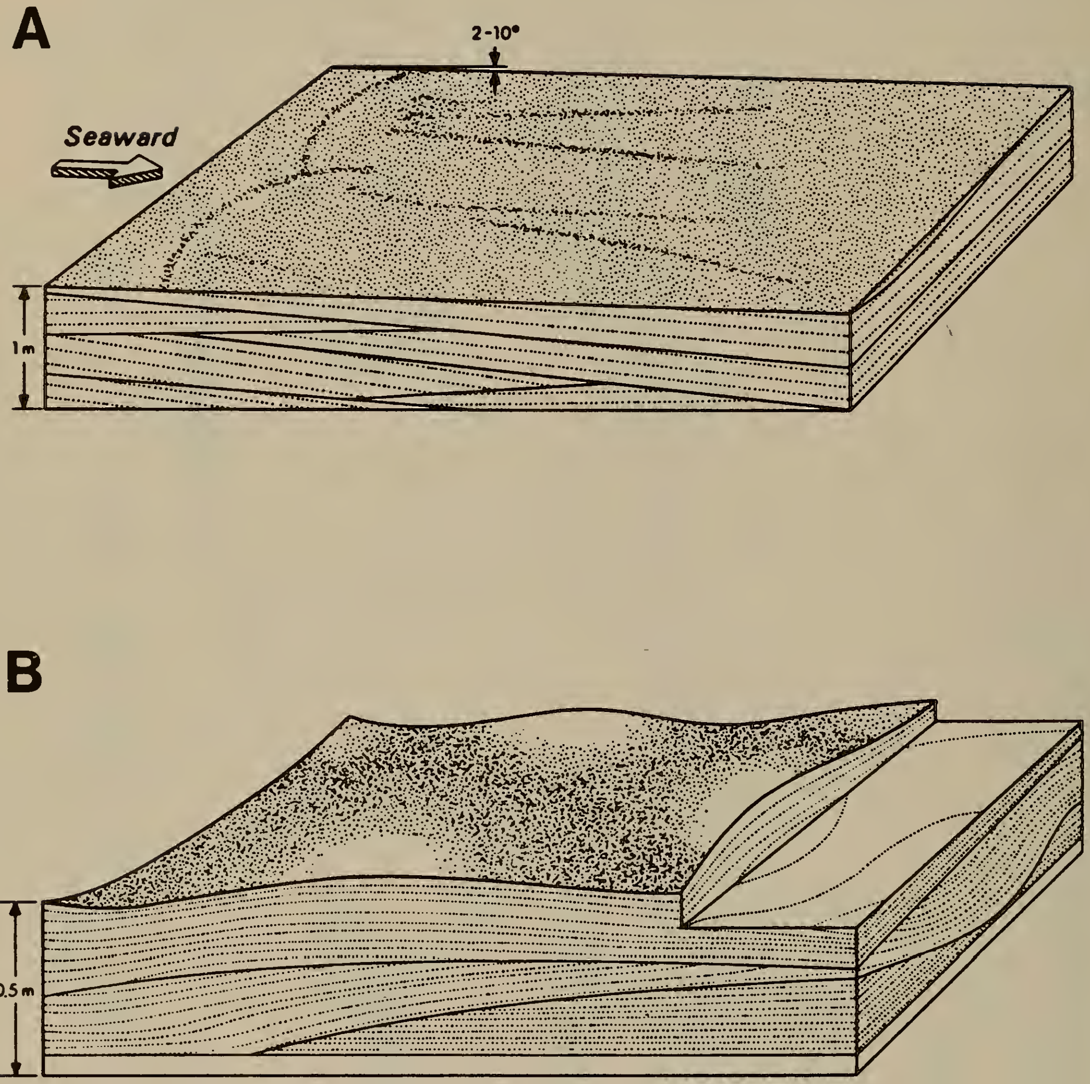


FIGURE 7. Beach and shoreface stratification types (modified from Harms et al., 1975).

A. Swash-generated stratification, the most common type found in berms. Note the low-angle truncations.

B. Hummocky cross-stratification, thought to be formed on the shoreface by storm waves.

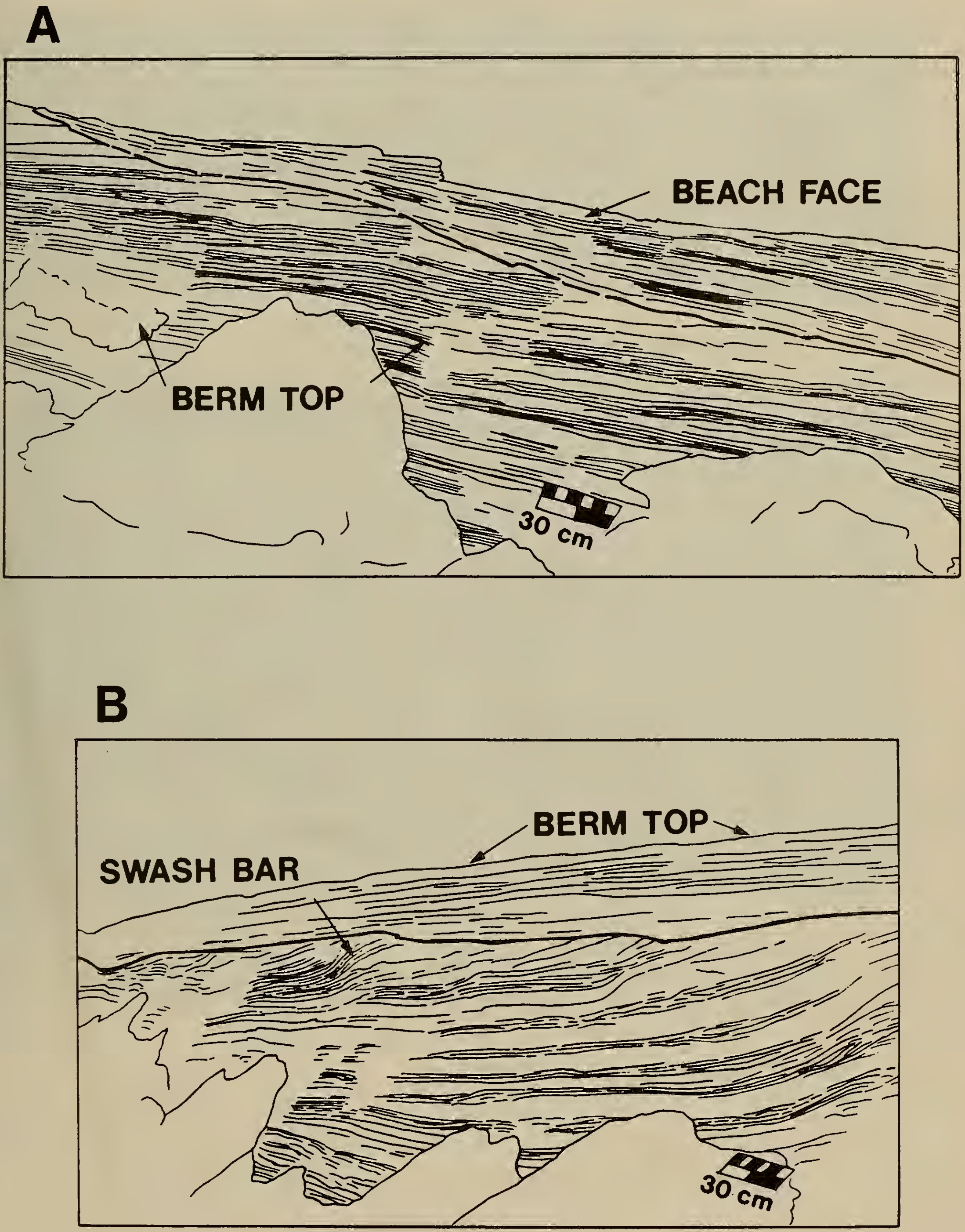


FIGURE 8. Sketches of trench faces illustrating stratification types (modified from Hine and Boothroyd, 1978).
A. Beachface and berm top stratification.
B. Tabular cross-stratification produced by a migrating swash bar, overlain by berm top strata.

melted and led to sediment collapse and formation of deformational structures. These sedimentary units are ice-contact lacustrine-fluvial morphosequences in the terminology of Koteff (1974) and Koteff and Pessl (1981).

Ripple-drift cross-stratification (climbing ripples) - The migration of cuspate ripples, utilizing the sediment supply of the bed alone, gives rise to the stratification seen in longitudinal section in Figure 4, i.e., sets of uneven thickness with erosional, and more or less horizontal top and bottom bounding surfaces. With the addition of sediment supplied from suspension, the ripples accrete upward as well as migrating forward. The preserved ripple form "drifts" or climbs at an angle to the horizontal. Jopling and Walker (1968) have classified the cross-stratification resulting from this type of ripple migration as follows:

1) Type A - high energy, low angle of climb, no stoss-side preservation;

2) Type B - low energy, high angle of climb, stoss and lee side preservation.

Draped lamination as defined by Gustavson et al. (1975), is a third type that is found when sediment fallout from suspension is deposited on the bed below the threshold of ripple migration. The three types are shown in Figures 9 and 10.

Turbidity Currents and Depositional Sequences - Studies by Ashley (1975), Gustavson (1975), Gustavson et al. (1975), Shaw (1975), and many other workers have shown that the stratification of glacial-lake deltas was formed by density underflow or turbidity-current flow. Sediment-laden meltwater plunged beneath the lake surface, down the delta front and prodelta slope, and out across the lake floor. Coarser sand was deposited nearer the source of the flow, fine sand and silt on the prodelta, and fine silt and clay on the lake floor to give a proximal to distal turbidite sequence. As the flow strength decreased in any one turbidity-current event, a sequence of Type A ripple-drift cross-stratification, followed by Type B, and then draped lamination would be deposited. This sequence ranging in thickness from 10 - 50 cm, is deposited in a matter of a few hours according to Ashley et al. (in press). Figure 10 illustrates a typical sequence.

Varves - Varves, defined as silt/clay couplets deposited in one year, were shown by Ashley (1975) to be deposited by the distal portion of turbidity currents. Prodelta ripple-drift sequences are sometimes bounded on the top and bottom by clay layers, and may be considered proximal varves. Both distal and proximal varves may be seen in this pit, but can be difficult to decipher.

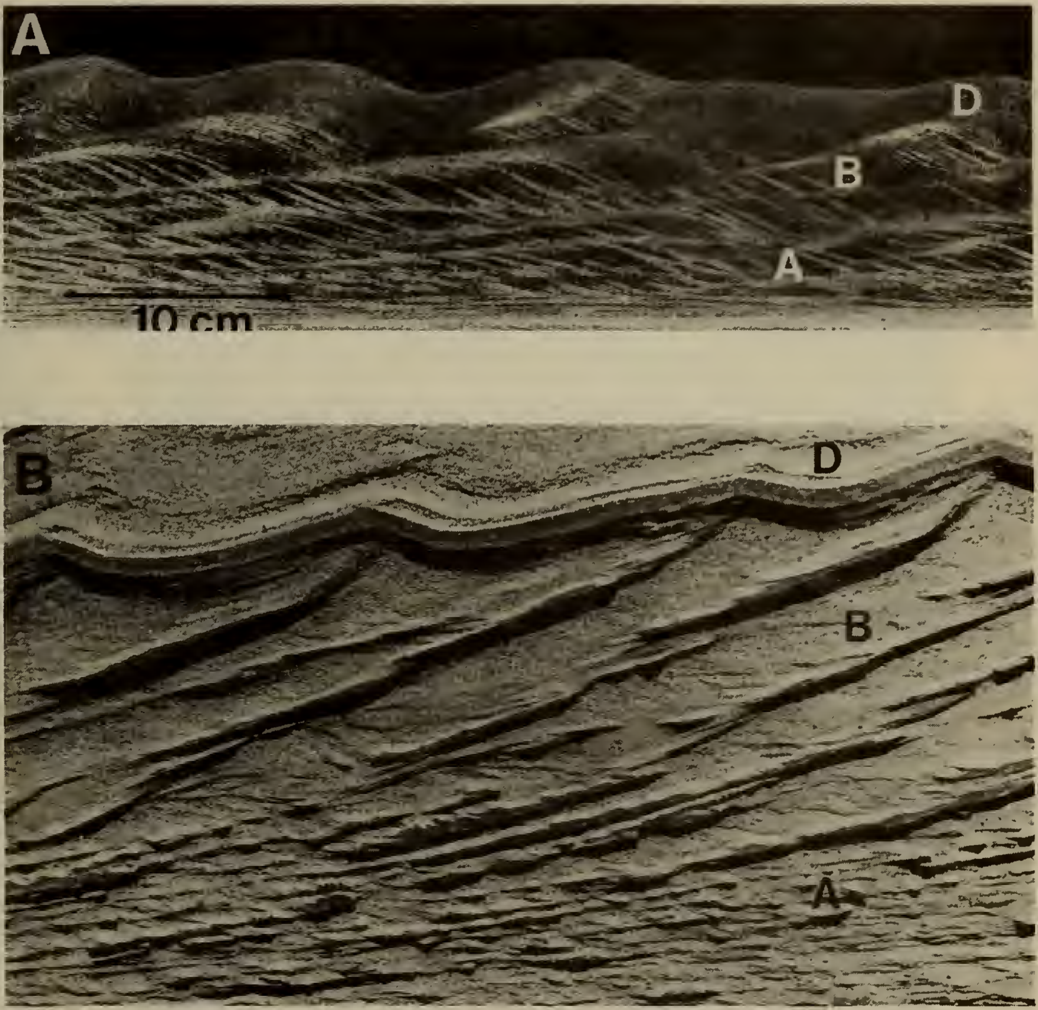

A
D
B
A
10 cm
B
D
B
A

FIGURE 10. A depositional sequence deposited by one turbidity-current event (from Gustavson et al., 1975).

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Itinerary

The trip will leave from the Keaney parking lot by the athletic fields, University of Rhode Island. The return to the University is by a different, and shorter route, than the trip out. Long-handled shovels, entrenching tools, and scrapers are mandatory to uncover and prepare the trenches and pit faces for proper viewing.

Distance (In Miles)		Route and Stops
Pt. to Pt.	Total	
0	0	Leave Keaney parking lot, turn right (west) on RI 138.
0.6	0.6	Intersection of RI 110 at lights. Turn left (south) on RI 110. This route also called Ministerial Road.
3.8	4.4	Tuckertown Four Corners, intersection of Wordens Pond Road on the right (west), and Tuckertown Road on the left (east).
		On ice-contact deposit is just north of the Charlestown end moriane. Proceed south through the intersection and up onto the moraine.
0.7	5.1	Backside (ice-contact slope) of Charlestown moraine.
1.3	6.4	Intersection with old Post Road, and beginning of proximal outwash plain. Proceed south to US 1.
0.2	6.6	US 1, go west past exits to Moonstone, Green Hill, and Charlestown Beaches.
4.3	10.9	RI 2 exit (north).
2.0	12.9	Exit to former Charlestown Naval Air Station and to Burlingame State Camping Area. The Air Station (now closed)was the proposed site for a nuclear generating station.
0.9	13.8	View of Ninigret Pond, a coastal lagoon, to the left (south). East Beach barrier spit is visible south of the lagoon.
1.2	15.0	Exit left, across median strip at East Beach sign; also at Dunn's Corners Fire District, Station #2, Quonochontaug; and Quonochontaug Grange Hall. Go east on US 1, 0.1 mile to East Beach Road, turn right and proceed south.

1.2	16.2	East Beach barrier spit; turn left (east) and go to State parking lot.
0.2	16.4	STOP 1. East Beach barrier spit, a microtidal barrier dominated by overwash processes. The depositional beach profile exhibits a high, wide berm top and steep beach face. The post-storm recovery profile is a classic ridge and runnel, often with multiple "piggyback" swash bars. Salt marsh peat is well-exposed on the low-tide terrace after severe storm events. Deep trenches dug in the berm will expose stratification deposted during the storm and recovery cycles. Return to US 1.
1.3	17.7	US 1, turn right (east) go 0.2 miles to first U-turn in median, head west on US 1. Pass Quonochontaug, West Beach, RI 216, and Weekapaug Beach exits. Cross over the Charlestown moraine.
3.8	21.5	Dunn's Corner; go west through lights at intersection; pass the Westerly airport that is located on a kame plain north of the moraine.
2.0	23.5	Intersection (lights) with RI 78, Westerly Bypass. Turn right (north).
2.5	26.0	Exit 4, RI 3. Exit and turn left (south on RI 3.
0.7	26.7	T-intersection, turn right (north) on Potter Hill Road; pass under RI 78 to intersection with Boom Bridge Road.
0.6	27.3	Stop sign, Boom Bridge Road. Proceed straight through intersection (north).
1.3	28.6	Boom Bridge over Pawcatuck River; enter Stonington, Ct. Turn left just over bridge onto borrow pit access road. Note: secure permission from pit owner at the house nearest the pit entrance.
		STOP 2. Boom Bridge borrow pit. This pit is in Chapman Pond-Green Fall River glacial stream and lake depostis (Qgc4) of Schafer (1968). Depositional environment was a kame plain with numerous small kettlehole ponds that were filled by lake floor, and delta front and slope deposits, capped by fuvial gravel. Numerous active and inactive faces display proximal varves, and

abundant ripple-drift cross-stratification deposited on complexly interbedded delta lobes. Faulting, deformational structures, and rotated beds are locally abundant due to melting of buried ice. Flow till also is present. Extensive walking about is advised because the pit is 1/2 mile long with active workings that change often.

0.0	0.0	Easy route to U.R.I. Leave pit and proceed straight ahead (north) on Boom Bridge Road; do not turn back over the bridge. Go up hill onto a large kame plain; bear left at Anthony Road (0.8 miles) to stay on Boom Bridge Road.
1.1	1.1	Pass over I 95
0.5	1.6	Intersection with CT 184, New London Turnpike. Turn right (east).
0.6	2.2	Intersection with CT 216 and I 95. Turn right, go under I 95, turn left up the northbound on-ramp of I 95. Proceed north on I 95.
7.4	9.6	Exit 3A, to RI 138 east. Exit and turn right (east) on RI 138.
2.0	11.6	RI 112 intersection.
5.2	17.8	RI 2 rotary.
1.4	19.2	RI 110 intersection.
0.6	19.8	Keaney parking lot, URI

END OF TRIP

Advances, retreats, readvances, and surges in the glacial story of southern New England

Joseph H. Hartshorn
University of Massachusetts

To my colleagues who do not know much about the glacial geology of southeastern New England and for whom a modern summary article would have been useful, I apologize for not writing it. Such an article could only be written by J. P. Schafer, whose lifetime of work in this area is unmatched by any, but who was not available. Instead I have chosen to write briefly about a few of the problems of the Pleistocene in southern New England that we may encounter. If you feel the need for an overview, read Schafer and Hartshorn (1965), which is still the only general summary on the Quaternary of New England available.

More than 140 years ago E. H. Hitchcock gave the earliest real endorsement to the glacial theory in New England. Today, after innumerable field conferences and 72 (?) previous meetings of the NEIGC, the glacial geology of southern New England and the Quaternary history it reveals are still largely unresolved. The field trips we glacial (or Quaternary) geologists will undertake here at this 1981 meeting of the NEIGC will show us several aspects of glacial process and stratigraphy. Skepticism is invited. After all, geology is still growing and adding new hypotheses. Publication of maps or articles do not render truth, but they are tangible platforms on which to build. Progress in glacial geology is fitful; it acts like the glacier itself--in advances, retreats, readvances, and, to make the most far-out comparison, surges.

In 1976, I listed what seemed to me to be the major unsolved problems in the New England Quaternary (Hartshorn, 1976). Those problems, in brief, are the number and extent of the glacial advances, the ages of the tills, the origin of the upper and lower tills, the details of deglaciation, the paucity of meaningful radiocarbon dates, the origin and meaning of glaciofluvial sequences (for which I would now substitute morphosequences, see Koteff and Pessl, 1981, p. 6), the late-glacial and postglacial isostatic readjustment. At that time I was somewhat pessimistic about resolving these problems and suggested that old-fashioned detailed quadrangle mapping seemed to be the solution. Today I am more optimistic. It is true that quadrangle mapping has provided the basic data for larger scale interpretations, and it also is clear that those geologists with this kind of experience have lately been able to expand their data base as they compile maps of larger areas, so that we are experiencing a readvance in knowledge once more.

From the earliest studies in New England, the ideas on how the glaciers accomplished the results we see in today's landscapes have waxed and waned as fitfully as the glaciers themselves. Some of the ideas on glacial history or processes have gone essentially in one direction (an advance). For instance, after the early statements about the advance of the ice sheet to the two great outer moraines (Chamberlin, 1883), the first maps of the "terminal" moraines on Cape Cod showed the moraines extending continuously from the Elizabeth Islands (or Woods Hole if we insist on remaining on the mainland of the Cape) all the way around the western, northern, and eastern sides of the Cape, and as far north as the modern beach and dune area of Provincetown. The myth of the "interlobate moraine" extending up the forearm of the Cape lingered for many years (Mather, 1952), despite Grabau's (1897) recognition of the great westward-sloping outwash-delta plains fed from the easternmost lobe of the ice. Since those early ideas, the moraines have shrunk to the Sandwich and Barnstable Moraines (Woodworth and Wigglesworth, 1934) and most lately to the present interpretation, in which the moraine ends to the east in Yarmouth (Oldale, 1974). In these interpretations, we have seen a steady retreat in the extent of the moraine, a result of detailed mapping on the increasingly better maps as the U.S.G.S. went from 1:62,500 to 1:24,000 and from 20-foot to 10-foot contour intervals.

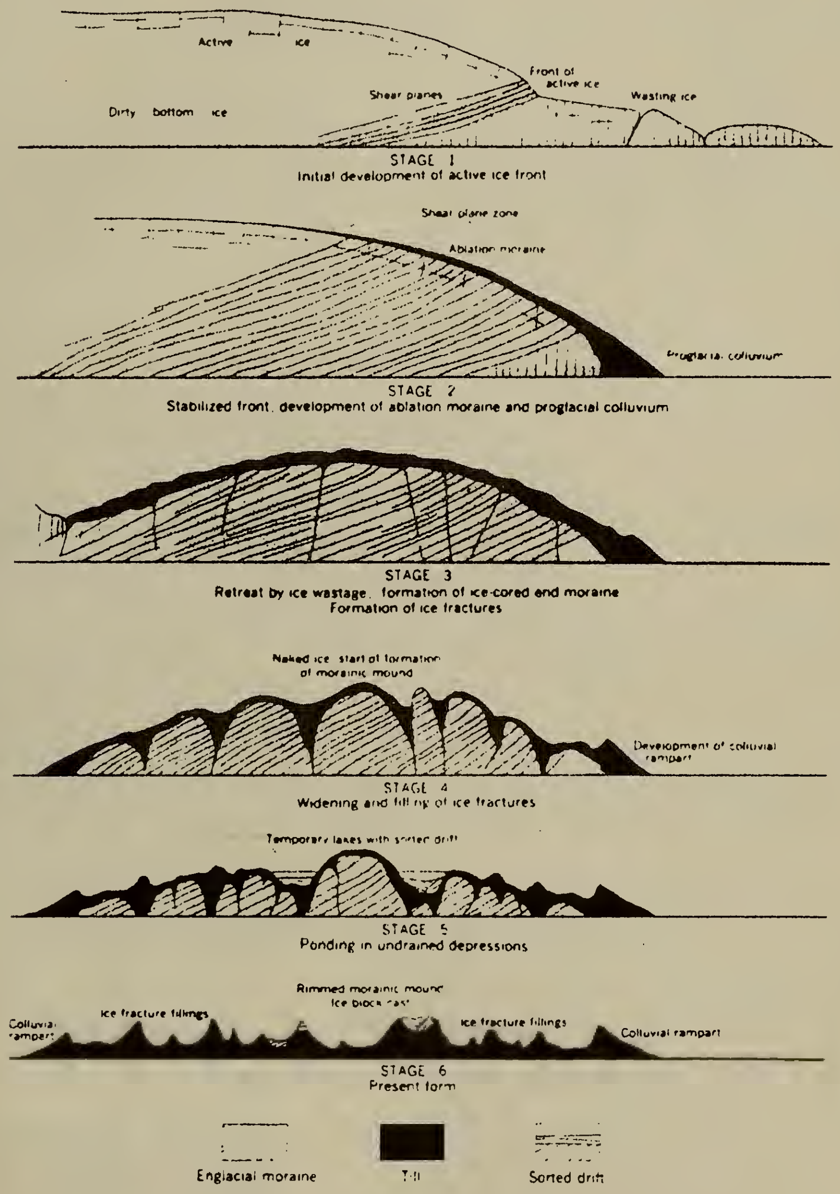
With the better maps, ideas about the nature of the end moraine have changed. The Charlestown Moraine, which we will visit, was long thought of as an ordinary pile of debris pushed up at the terminus of a normally retreating glacier. Tectonism on a small scale is usually implied in the term moraine; the ice pushes up a ridge of generally unstratified debris in front of it. Kaye (1960), however, using air photos and modern maps, took a closer look at the internal textures and structures and external forms of the Charlestown Moraine and gave us different ideas about the great load of debris deposited at the stagnant margin of the receding ice and the subsequent development of an array of stagnation phenomena: ice-block casts, deformed lake deposits with flowtill, marginal ridges or colluvial ramparts, and variously oriented till ridges or ice-fracture fillings within the borders of the moraine. Schafer's later work (1965) at Watch Hill, R.I., extended the work of Kaye to the west; his map explanation implies the same origin given by Kaye. Although no retreats from Kaye's ideas have been documented, still a residue of doubt exists. Can that huge moraine--2 miles wide at its east end, mostly about a mile wide, although narrowing to about a third of a mile; about 20 miles long; with ridges of from a few feet to 80 feet high and (in the Kingston quadrangle) 1 to 2 miles long; and numerous roughly circular mounds tens of feet high--have formed from the debris brought to the glacier terminus during the limited number of years available to build that moraine? And could that much debris be incorporated in a stagnant ice zone with no replenishment (Figure 1)?

The amount of debris that must be carried to the end and to have accumulated supraglacially on that ephemeral stagnant ice margin in order to produce such large features is staggering. Still, if we wish to retreat from Kaye's ideas prior to a readvance or surge in knowledge, what better solutions have been offered? The "dirt machine" of Koteff and Pessl (1981) would be sufficient to bring debris, perhaps, but where is the evidence of meltwater runoff?

A waxing, waning, and waxing of ideas in glacial history has occurred in the mapping of minor moraines. Although Black (1981) denies the presence of several lines of moraines along the southern coast of Connecticut, it is clear that in general our ideas have turned from one of no moraines (save Fishers Island as part of the Charlestown-Harbor Hill morainic complex) to one where Goldsmith (1981) sees segments of moraine comprising five separate named moraines, several of which are double.

Some early maps of Massachusetts (Antevs, 1922) depicted linear end moraines, which were later ignored in part (Hartshorn, 1967) in favor of the idea that they were a series of high kames emplaced, for whatever reason, in a

Figure 1. Schematic north-south cross section of the Charlestown Moraine (Fig. 56 from Kaye, 1960, p. 367). U.S. Geological Survey.



number of areas and parallel to the ice front. Thus the Middleborough Kame Moraine of Mather (1952) retreated from the scene only to readvance again in Larson (1981). Certainly the geologist recognizes notable morainic segments (Koteff, 1964) and has mapped them. Now the question here, as in the Connecticut Valley (Hartshorn and Koteff, 1967; Larsen and Hartshorn, 1981), is how to align high kames along the margin of a retreating ice mass. They then are perhaps not moraines in the classic sense, but must somehow be related to the terminus of the ice sheet (Stone and Peper, 1981).

The large surficial maps at 1:125,000 in Connecticut and 1:250,000 in Massachusetts, now being compiled by the U.S.G.S., may signal a surge, or at least a readvance, in the mapping and interpretation of moraines in southern New England. The field trips led by Les Sirkin and J. P. Schafer at this 73rd (1981) meeting of the NEIGC should leave us with as many questions as answers.

Another area of glacial interpretation that has undergone changes of direction is the mode of deglaciation. We generally subscribe to a general retreat to the northward, with thinning of the ice and the appearance of nunataks near the margin. Some have viewed the ice as active to the outermost parts (Lougee, 1951); others, however, use the doctrine of stagnation-zone retreat (e.g., Jahns, 1941; Koteff, 1964; Koteff and Pessl, 1981). For a short period, R. F. Flint of Yale, as a young man, misled by bad topographic maps and his own misinterpretation of field evidence, advocated a north-to-south retreat, which he quickly disavowed. A major geological opponent (thoroughly ignored by Flint), R. J. Lougee of Clark, never ceased to point out his lapse from grace. This controversy of the 1930's may now be renewed in a modified form in the 1980's as Black (1981) minimizes the concept of stagnation-zone retreat, except in local areas. He envisions regional thinning and basin-by-basin stagnation, with marginal retreat of inactive ice. May the arguments be long, detailed, furious, yet restrained and Friendly. Lougee, whose emphasis on "hinge lines" led him to devise a unique chronology for the late-glacial history of New England (Lougee and Lougee, 1976) that stands entirely alone, used as his most valued mapping (and process) criterion the contact between the topset and foreset beds of deltas or deltaic kame terraces (altitudes sometimes inappropriately measured to the hundredths of a foot; Lougee, 1971). New England geologists have always recognized the deltaic contact, never giving it the interpretation or the importance Lougee did in the many glaciofluvical-appearing stream valleys of southern New England. Lately, U.S.G.S. surficial quadrangle maps have been published that extend some of Lougee's ideas on that contact, as well as using much other substantial geologic data, to show the ubiquity of glacial lakes and ponds, for instance in southeastern Massachusetts (Volckmann, 1975; Stone and Peper, 1981). But where Lougee saw only marine water bodies with uptilted marine terraces, present-day workers see topographically controlled extensive river-valley lakes, held in by bedrock, till, or ice spillways or outlets, whose bottom deposits are commonly covered by glaciofluvial sands and gravels of topset beds or graded deposits on the lake beds.

Lately the vexing problem of the tills of New England underwent a long series of advances, retreats, and readvances. After a lengthy history of debate, traceable at least back to Upham, the problem of whether we have a general blanket that includes a lodgement till/superglacial till section (the lower till below the upper till) or two tills from different ice advances and different times (old till below the new till) is still with us. We have had continuous controversy until the present time. The multiple-advance-till faction (e.g., Pessl and Schafer, 1968; Newton, 1978) seems to be leading the way. As usual, part of the recent controversies centered around misunderstandings. The idea that one of the till sheets in the controversy (the Bakersville Till studied by Pessl and formally named by Newton) commonly turned out to have a less sandy lower and a more sandy, commonly stratified upper facies helped to confuse things throughout the whole of New England. If, then, we cannot even separate or identify the lithologic unit to which a till belongs, how can we map in detail the till deposits of the area? So far, we have not.

It is obvious that we have not solved all, or even most, of the problems in New England. A field trip can only be a progress report. Of the three trips that specialize in glacial geology, Block Island and Glacial Geology in Southern Rhode Island will touch on many of the controversial areas. The trip on Interpretation of Primary Sedimentary Structures will concentrate on process, but within features whose place in the late-glacial history is perhaps not fully known. Together they should leave us with an appreciation of the problems found in the glacial geology of southern New England.

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